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Gagne et al.

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(54) COAXIAL LOCAL OSCILLATOR GENERATION AT A CONJUGATE FOCAL PLANE IN AN FMCW LIDAR SYSTEM

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G01S 7/4912	(2020.01)
G01S 7/481	(2006.01)
G01S 7/499	(2006.01)
G01S 17/34	(2020.01)

(52) **U.S. Cl.**
CPC ***G01S 7/4917*** (2013.01); ***G01S 7/4817*** (2013.01); ***G01S 7/499*** (2013.01); *G01S 17/34* (2020.01)

(58) **Field of Classification Search**
CPC G01S 7/4808; G01S 7/4811; G01S 7/4917; G01S 17/34
USPC 356/5.09
See application file for complete search history.

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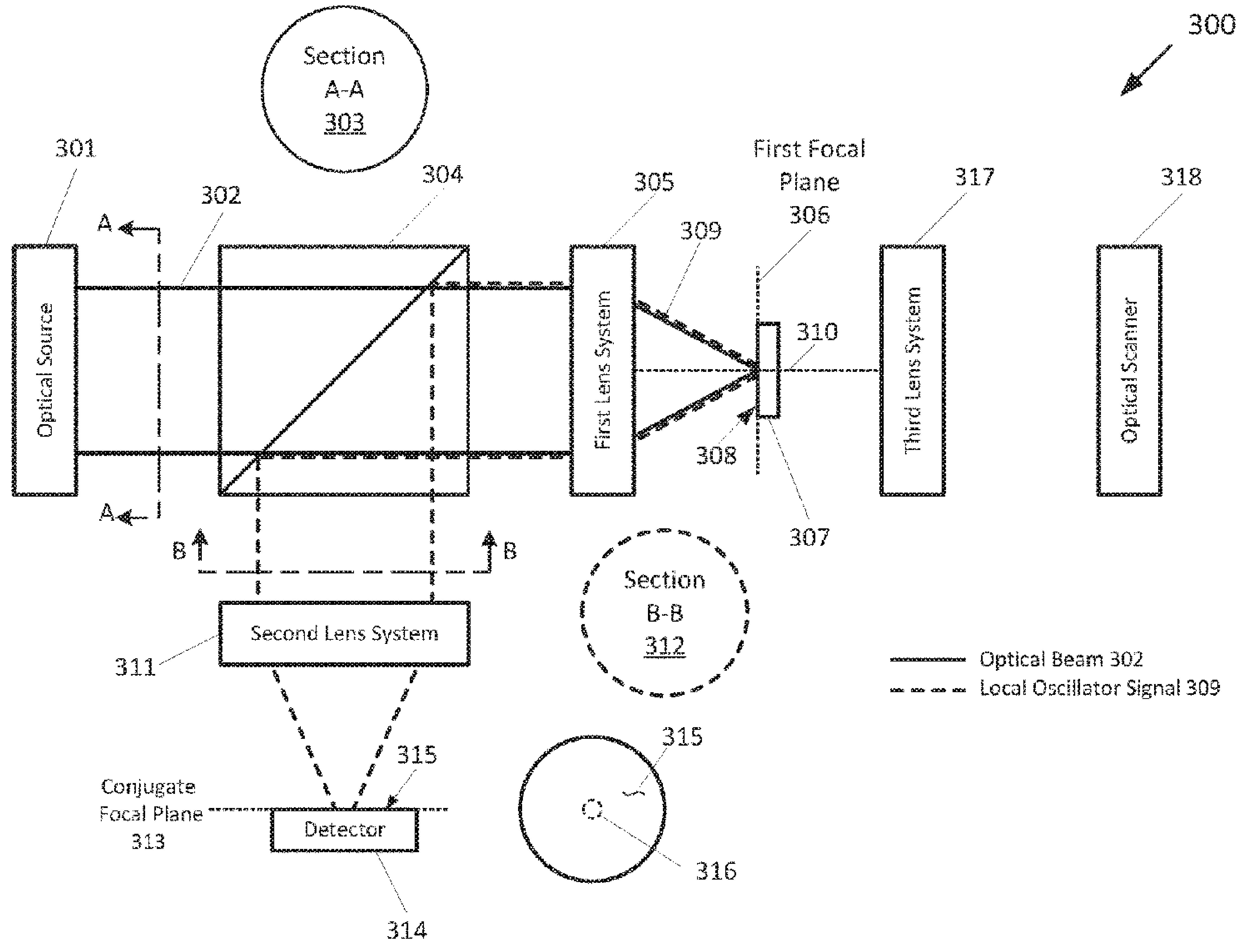
(57) ABSTRACT

A light detection and ranging (LIDAR) system includes an optical source to emit an optical beam, and free-space optics coupled with the optical source to focus the optical beam at a first focal plane, where a local oscillator (LO) signal is generated from a partial reflection of the optical beam from a partially-reflecting surface proximate to the first focal plane, and where a transmitted portion of the optical beam is directed toward a scanned target environment. The free-space optics configured to focus the LO signal and a target return signal at a second focal plane comprising a conjugate focal plane to the first focal plane. The system also includes a photodetector with a photosensitive surface proximate to the conjugate focal plane to mix the LO signal with the target return signal to generate target information.

17 Claims, 17 Drawing Sheets



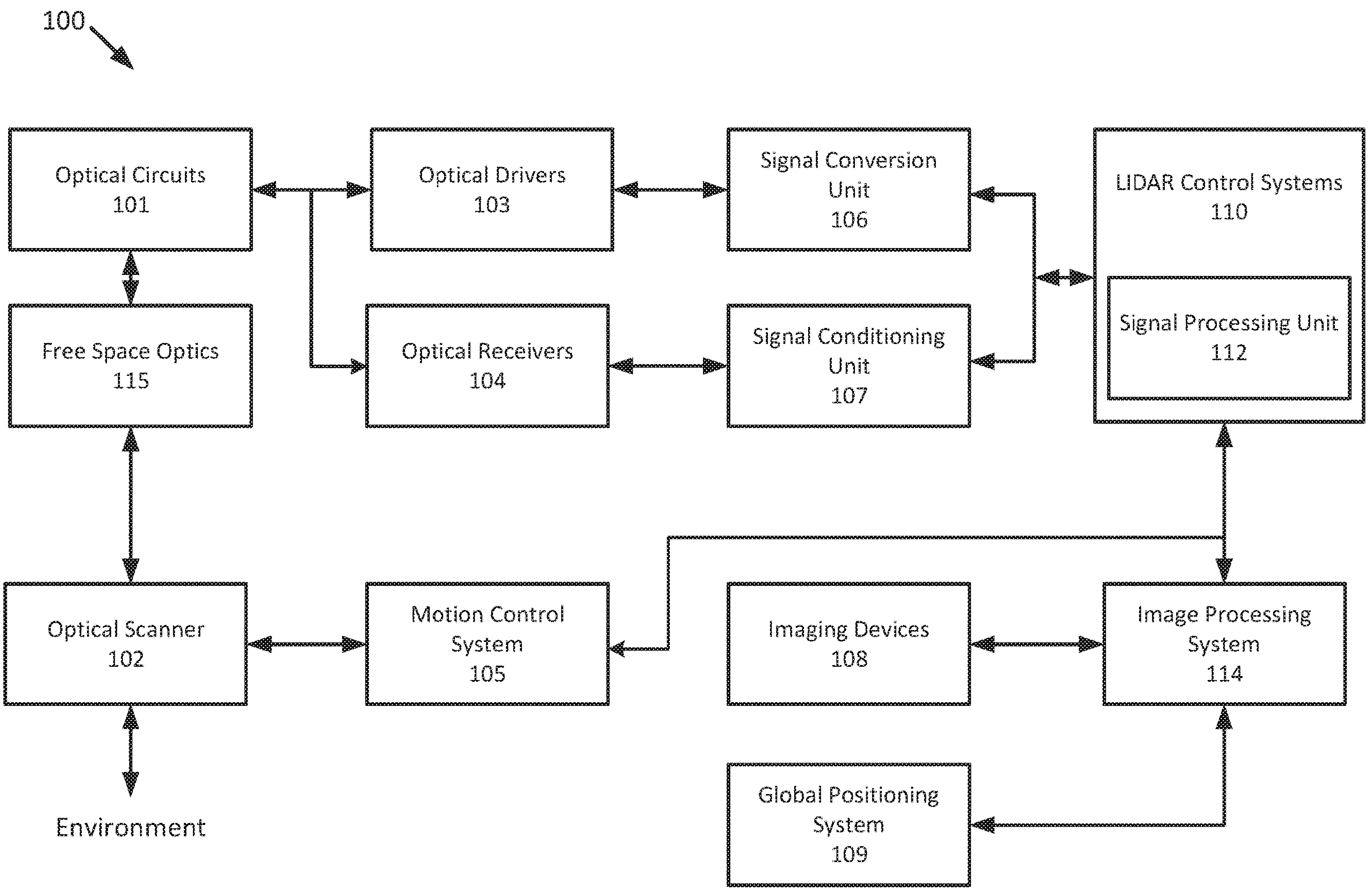

100
Optical Circuits
101
Optical Drivers
103
Signal Conversion
Unit
106
LIDAR Control Systems
110
Signal Processing Unit
112
Free Space Optics
115
Optical Receivers
104
Signal Conditioning
Unit
107
Optical Scanner
102
Motion Control
System
105
Imaging Devices
108
Image Processing
System
114
Global Positioning
System
109
Environment

FIG. 1

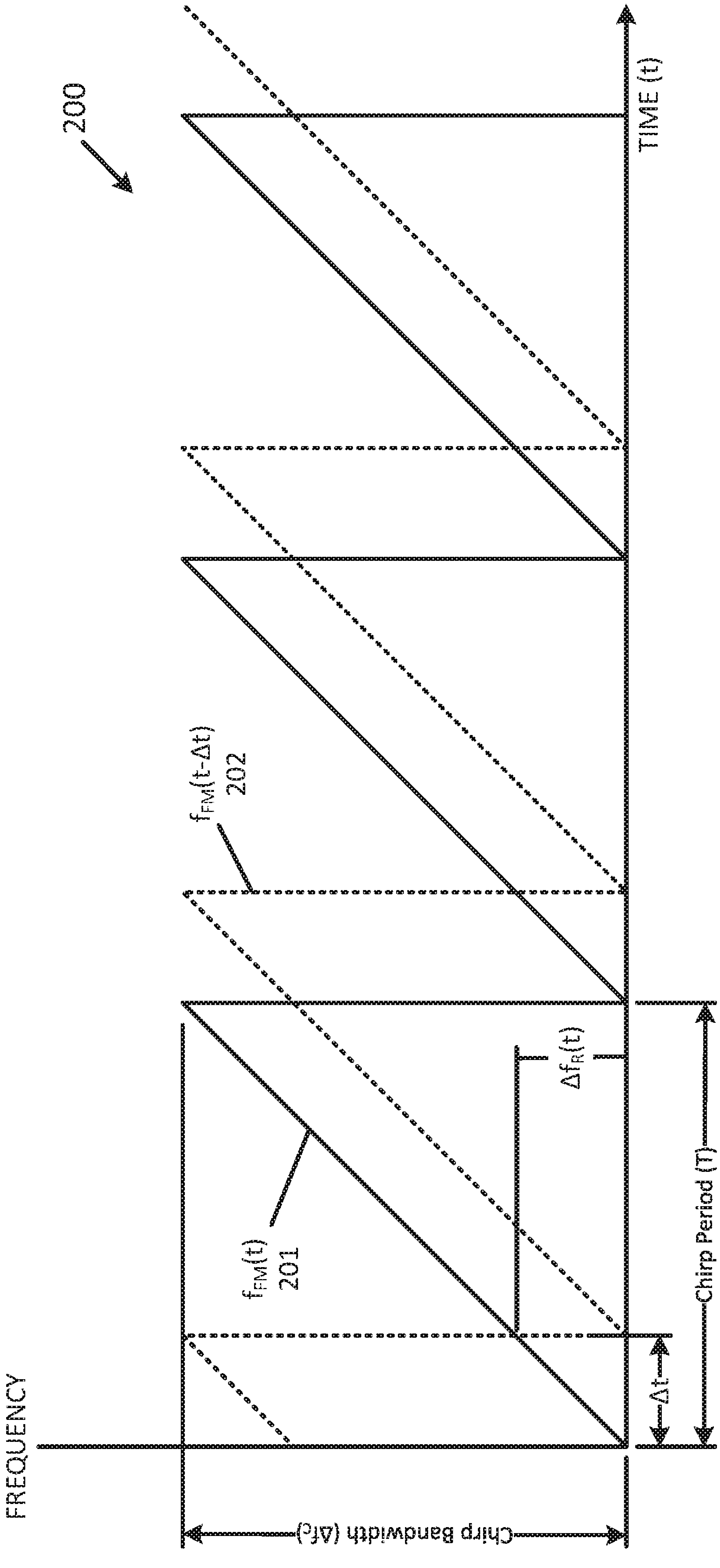

200
TIME (t)
FREQUENCY
$f_{FM}(t-\Delta t)$
202
$f_{FM}(t)$
201
$\Delta f_R(t)$
Chirp Period (T)
Δt
Chirp Bandwidth (Δf_C)

FIG. 2

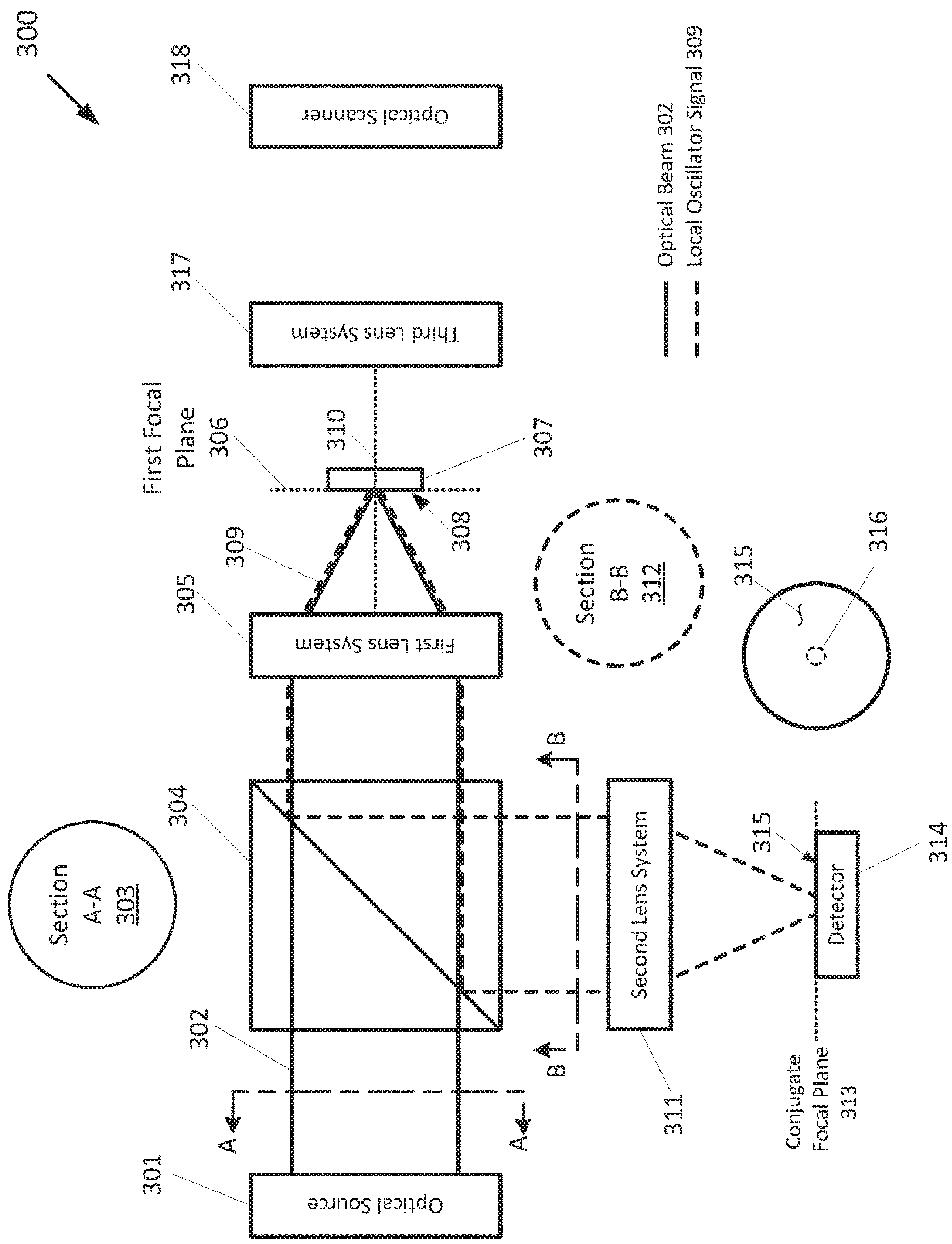

300
318
Optical Scanner
317
Third Lens System
First Focal Plane
306
310
307
308
309
305
First Lens System
Section B-B
312
315
316
304
Section A-A
303
302
A
A
B
B
Second Lens System
311
315
Detector
314
Conjugate Focal Plane
313
301
Optical Source
Optical Beam 302
Local Oscillator Signal 309

FIG. 3

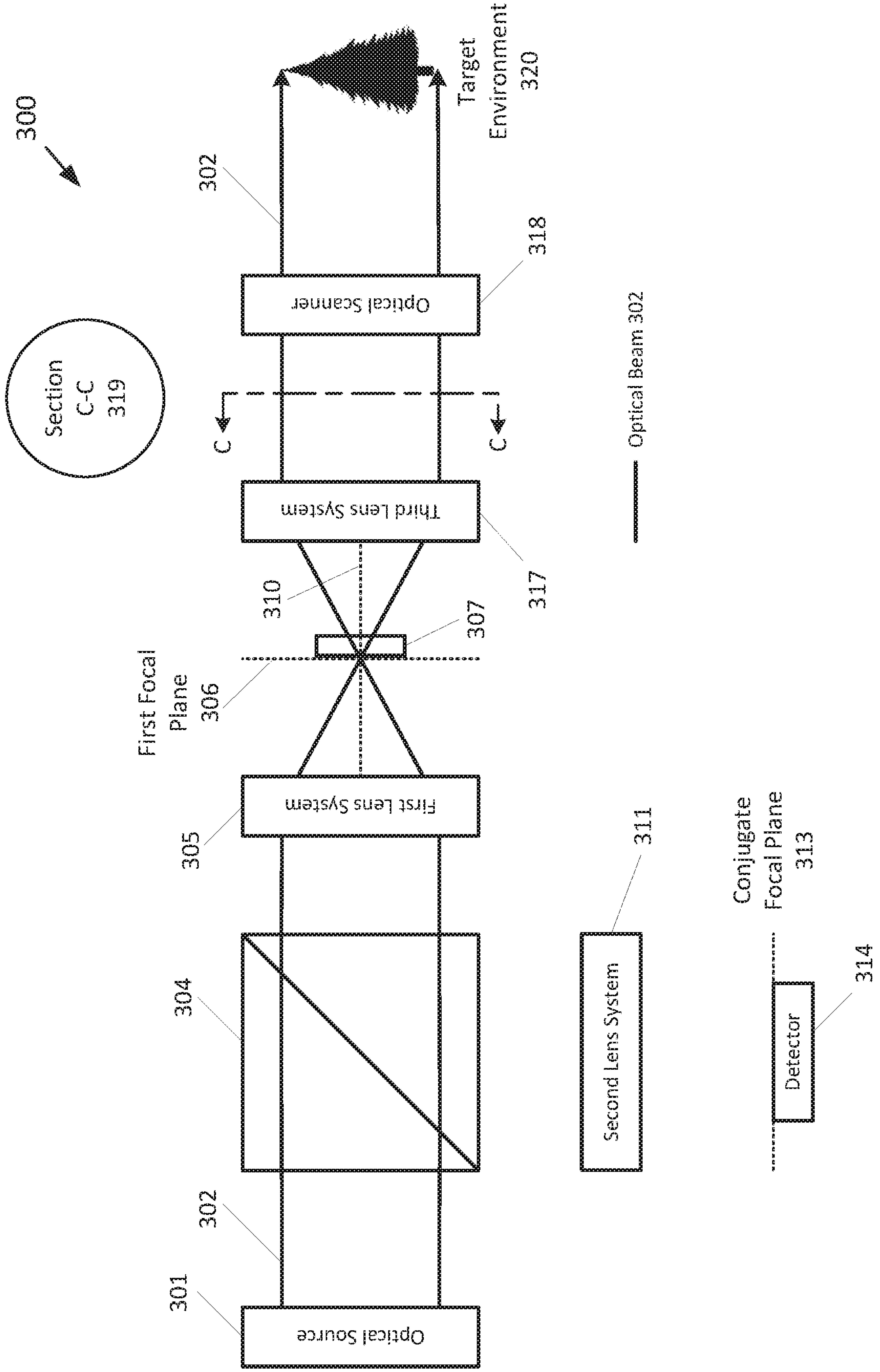

300
Section C-C 319
302
Target Environment 320
318
Optical Scanner
C
C
Optical Beam 302
Third Lens System
317
310
307
First Focal Plane 306
First Lens System
305
311
Conjugate Focal Plane 313
304
Second Lens System
314
Detector
302
301
Optical Source

FIG. 4

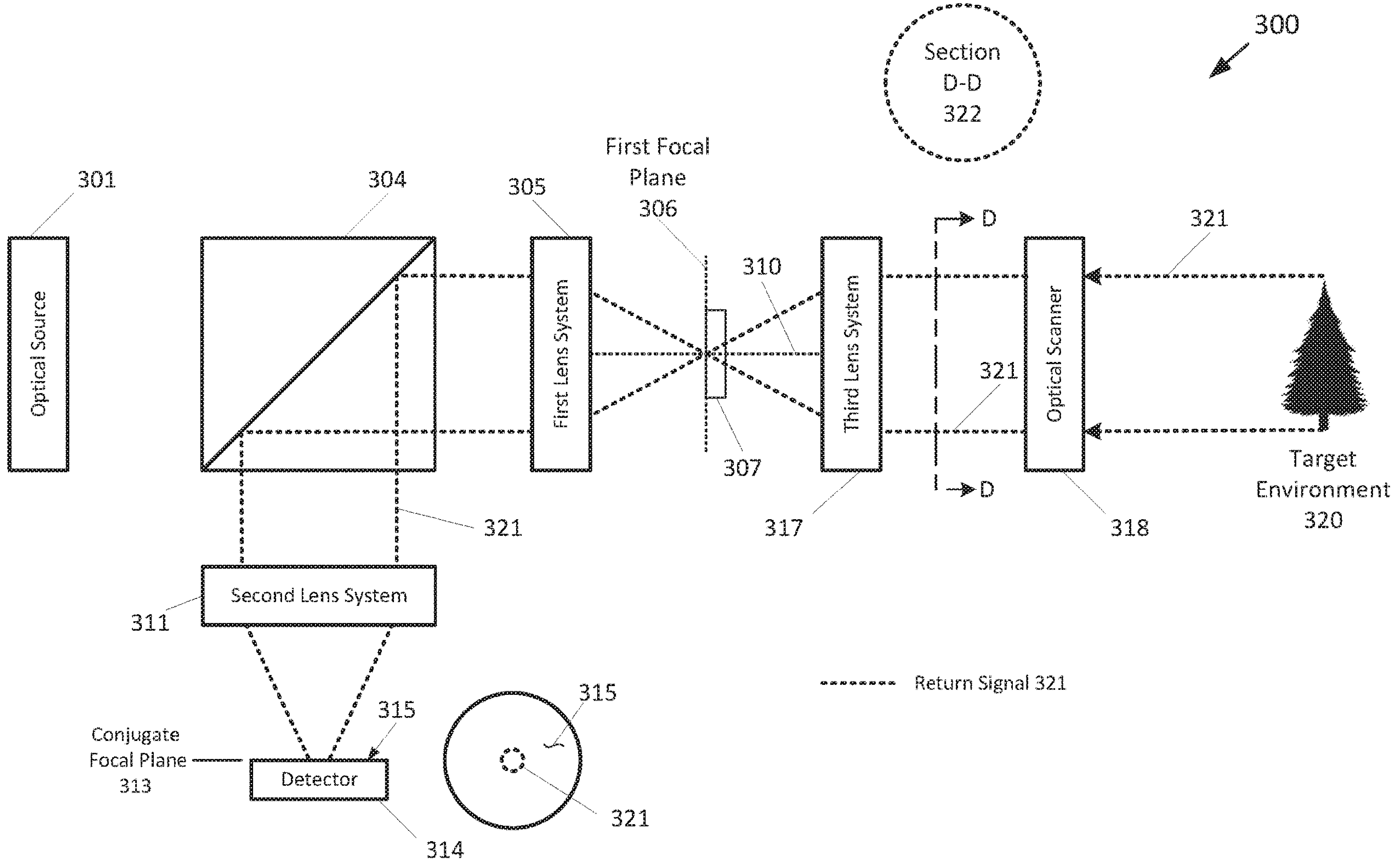

300
Section
D-D
322
301
Optical Source
304
305
First Lens System
First Focal
Plane
306
310
307
Third Lens System
317
D
D
321
Optical Scanner
318
321
Target
Environment
320
321
Second Lens System
311
Return Signal 321
Conjugate
Focal Plane
313
315
Detector
314
315
321

FIG. 5

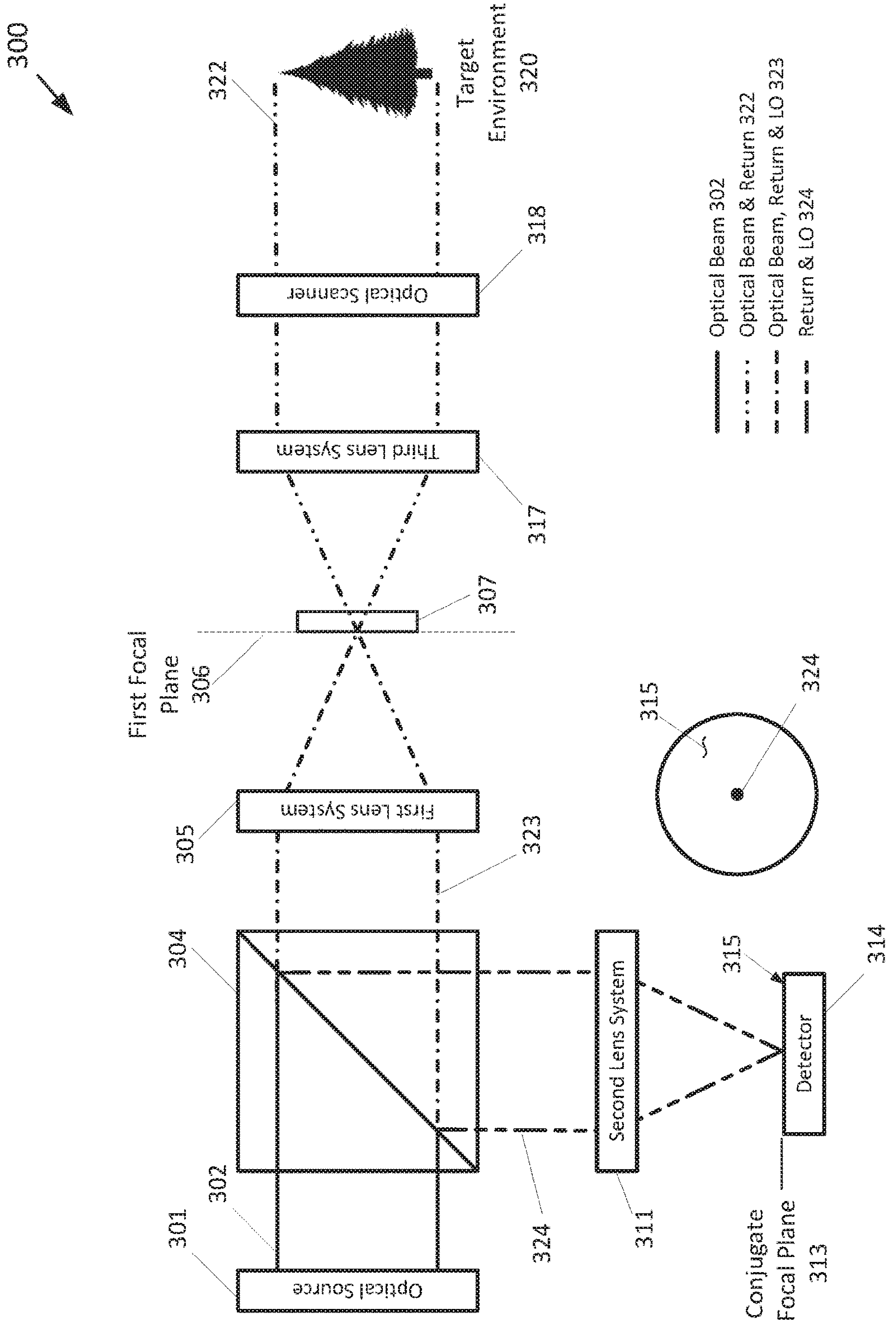

300
322
Target Environment 320
Optical Scanner
318
Third Lens System
317
307
First Focal Plane 306
First Lens System
305
323
304
302
301
Optical Source
324
Second Lens System
311
315
Detector
314
Conjugate Focal Plane 313
315
324
Optical Beam 302
Optical Beam & Return 322
Optical Beam, Return & LO 323
Return & LO 324

FIG. 6

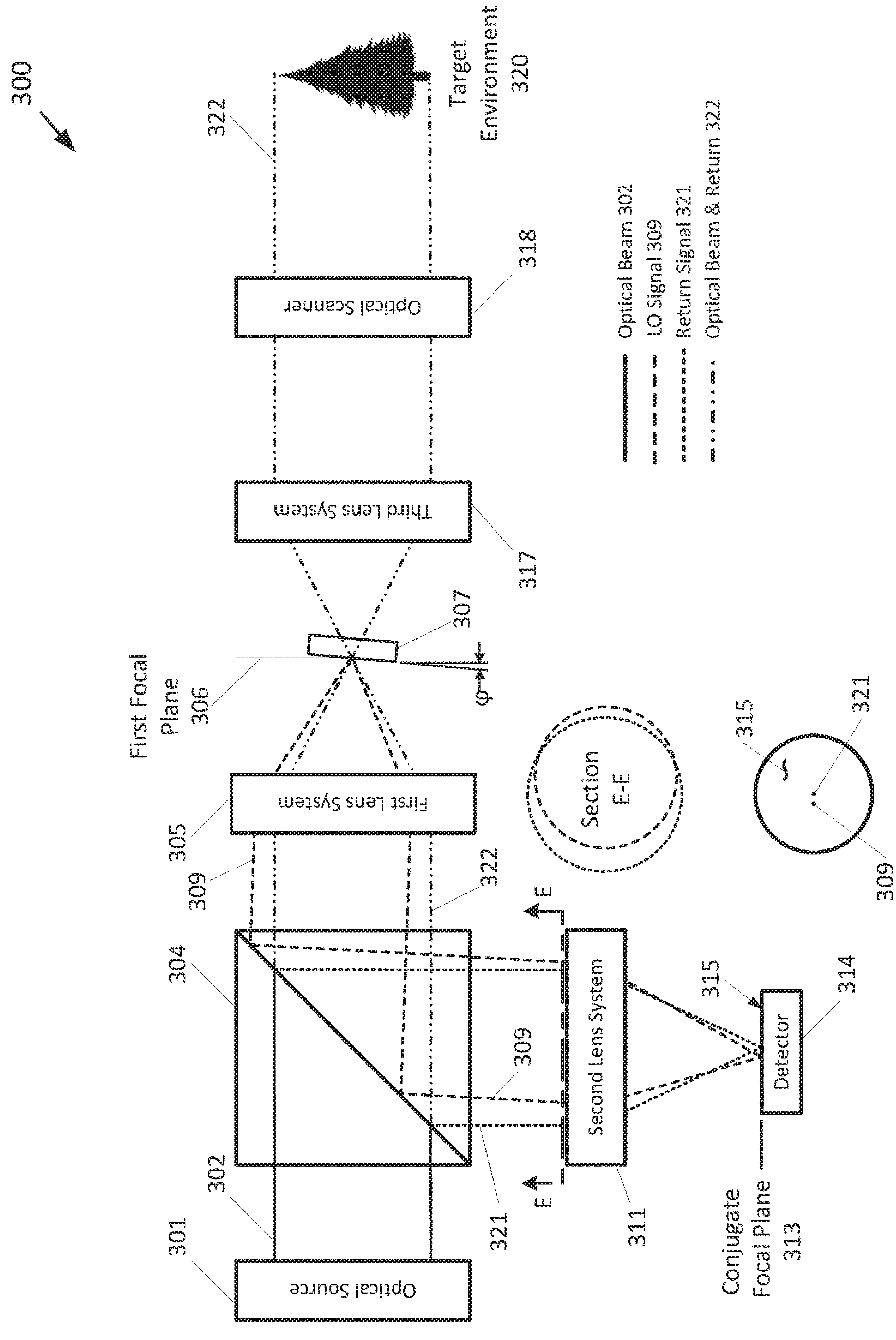
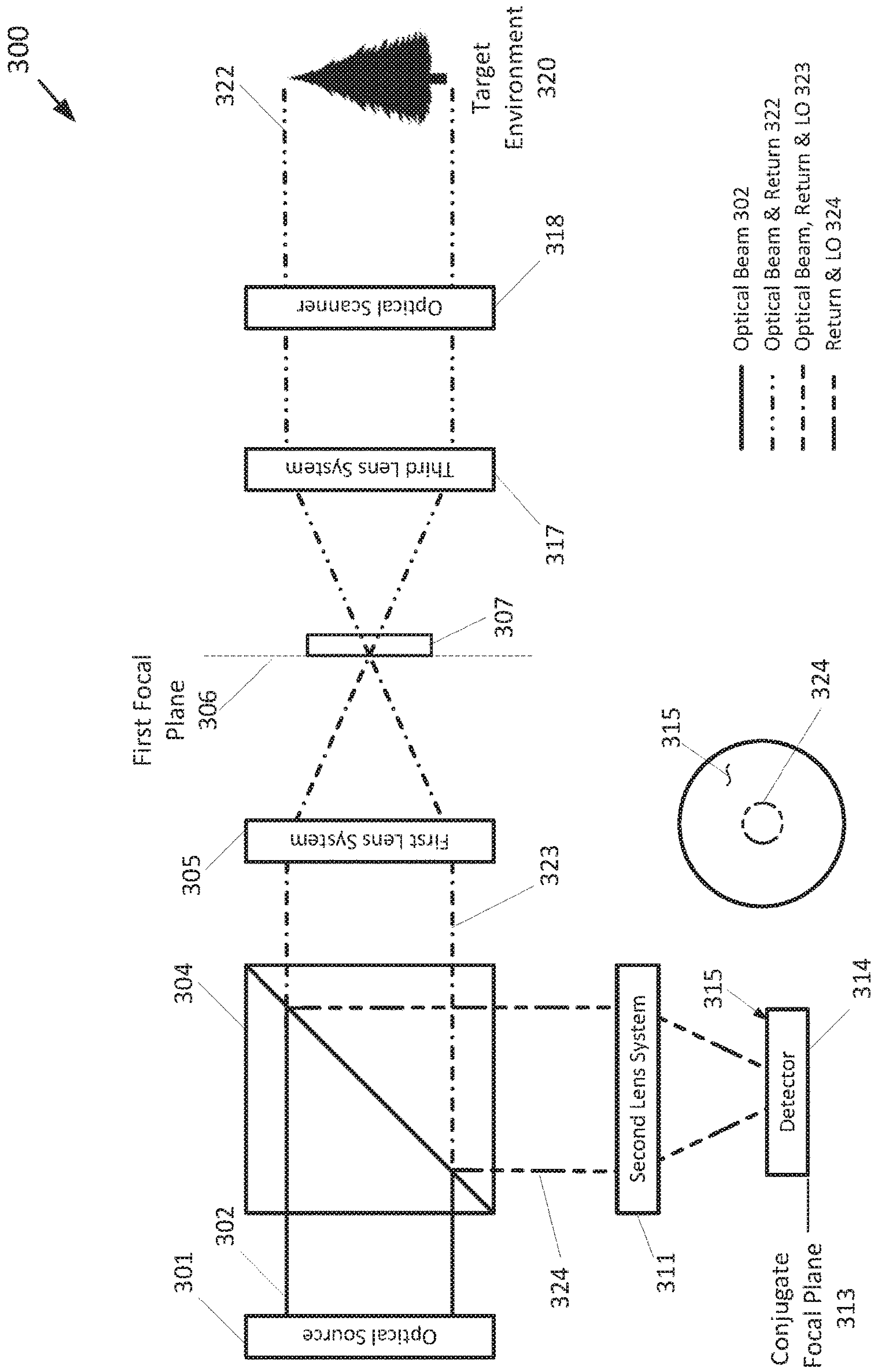

300
Optical Source
301
302
304
309
305
First Lens System
322
First Focal Plane 306
307
φ
Third Lens System
317
Optical Scanner
318
322
Target Environment 320
309
321
E
E
Second Lens System
311
315
Detector
314
Conjugate Focal Plane 313
Section E-E
315
321
309
Optical Beam 302
LO Signal 309
Return Signal 321
Optical Beam & Return 322

FIG. 7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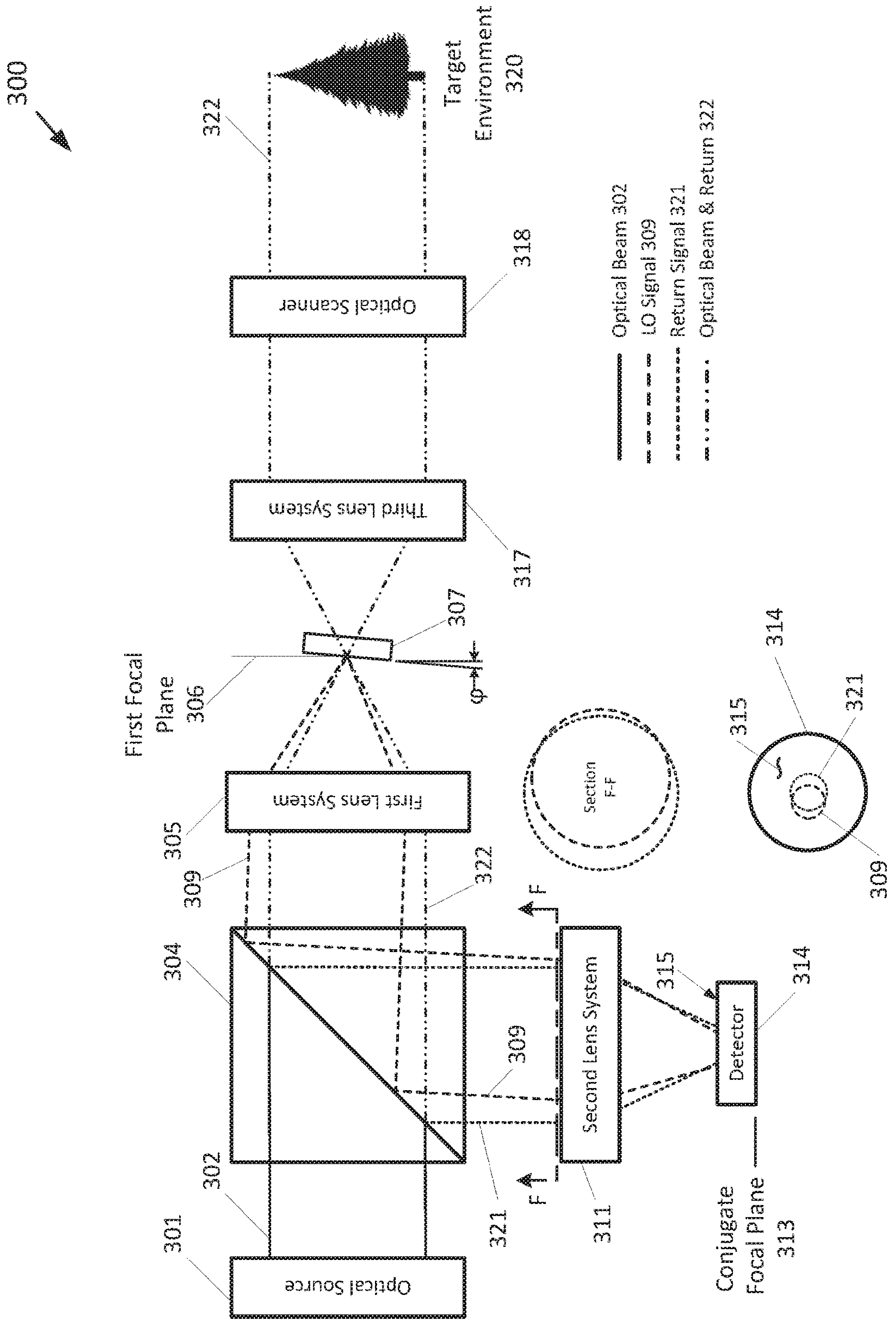
301
302
304
305
First Lens System
323
First Focal Plane 306
307
Third Lens System
317
Optical Scanner
318
322
Target Environment 320
324
Second Lens System
311
315
Detector
314
Conjugate Focal Plane 313
315
324
Optical Beam 302
Optical Beam & Return 322
Optical Beam, Return & LO 323
Return & LO 324

FIG. 8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Optical Source
301
302
304
321
309
Second Lens System
311
F
F
Detector
314
315
Conjugate Focal Plane 313
First Lens System
305
309
322
First Focal Plane 306
307
φ
Third Lens System
317
Optical Scanner
318
322
Target Environment 320
Section F-F
315
314
321
309
Optical Beam 302
LO Signal 309
Return Signal 321
Optical Beam & Return 322

FIG. 9

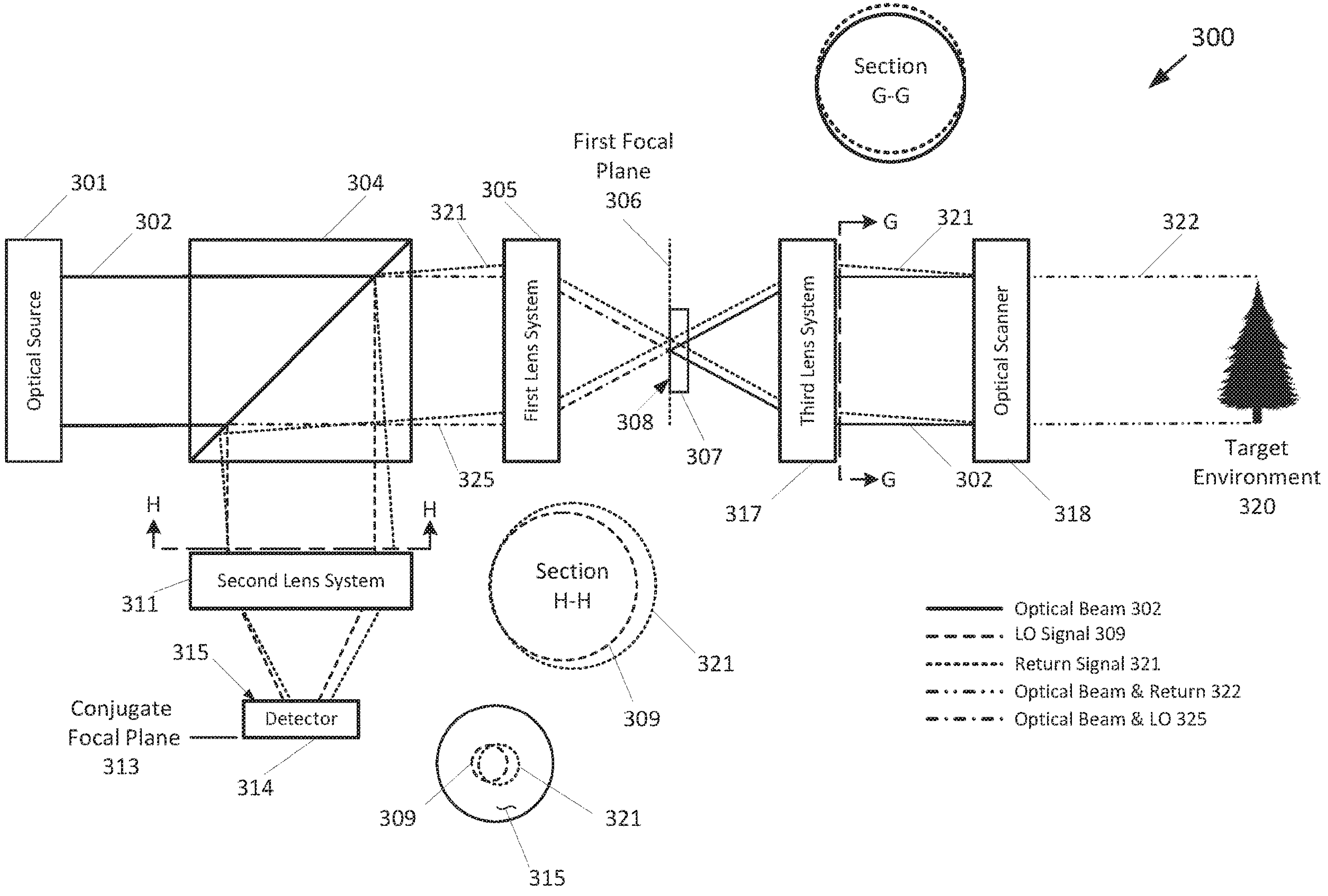

300
Section G-G
301
302
304
321
305
First Focal Plane 306
321
G
G
322
Optical Source
First Lens System
Third Lens System
Optical Scanner
308
307
325
317
302
318
Target Environment 320
H
H
Second Lens System
311
Section H-H
321
309
315
Conjugate Focal Plane 313
Detector
314
309
321
315
Optical Beam 302
LO Signal 309
Return Signal 321
Optical Beam & Return 322
Optical Beam & LO 325

FIG. 10

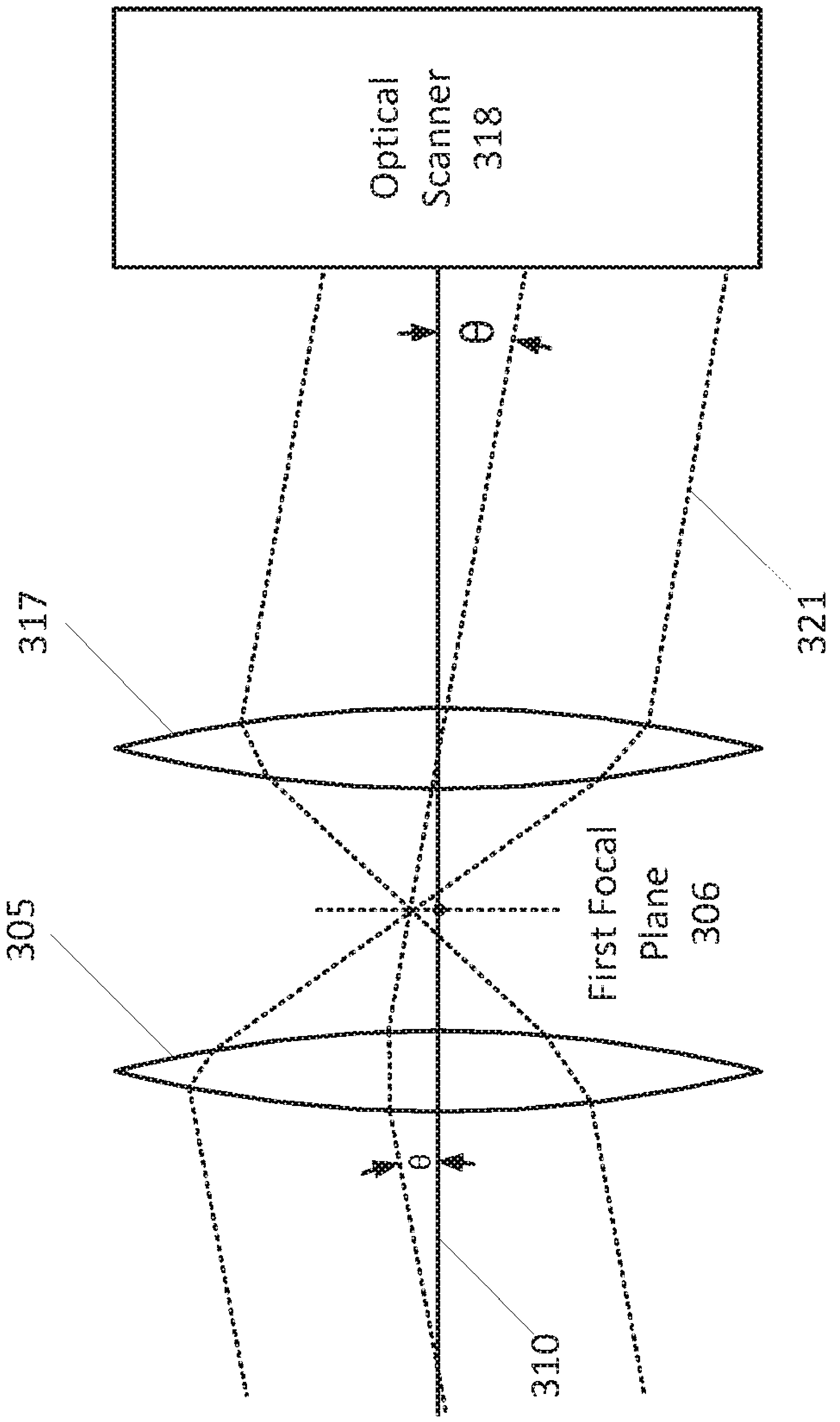
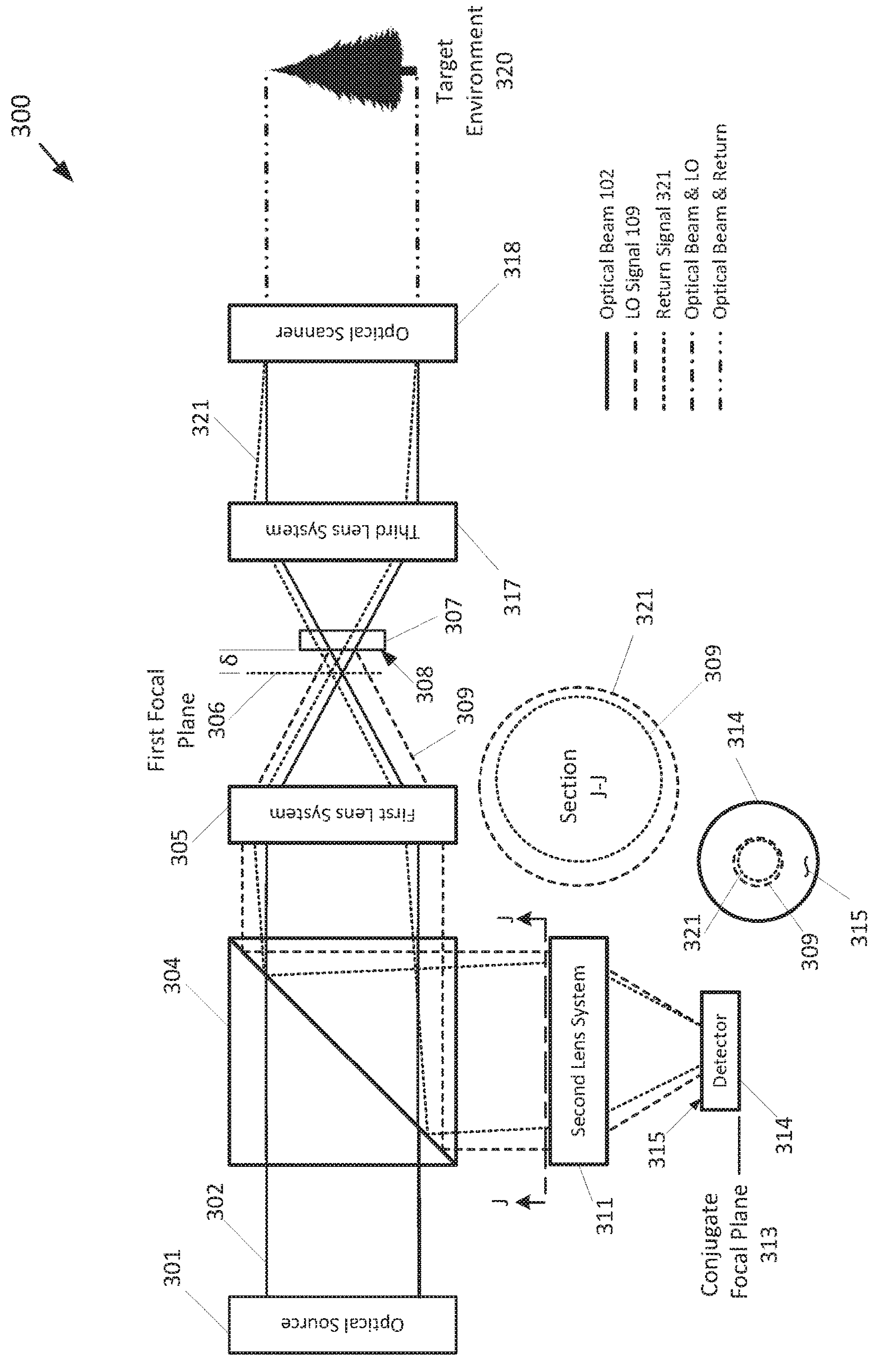


FIG. 11


300
Optical Source
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302
304
First Lens System
305
First Focal Plane
306
δ
307
308
309
Third Lens System
317
321
Optical Scanner
318
Target Environment
320
Second Lens System
311
J
J
Detector
314
315
Conjugate Focal Plane
313
Section J-J
321
309
314
321
309
315
Optical Beam 102
LO Signal 109
Return Signal 321
Optical Beam & LO
Optical Beam & Return

FIG. 12

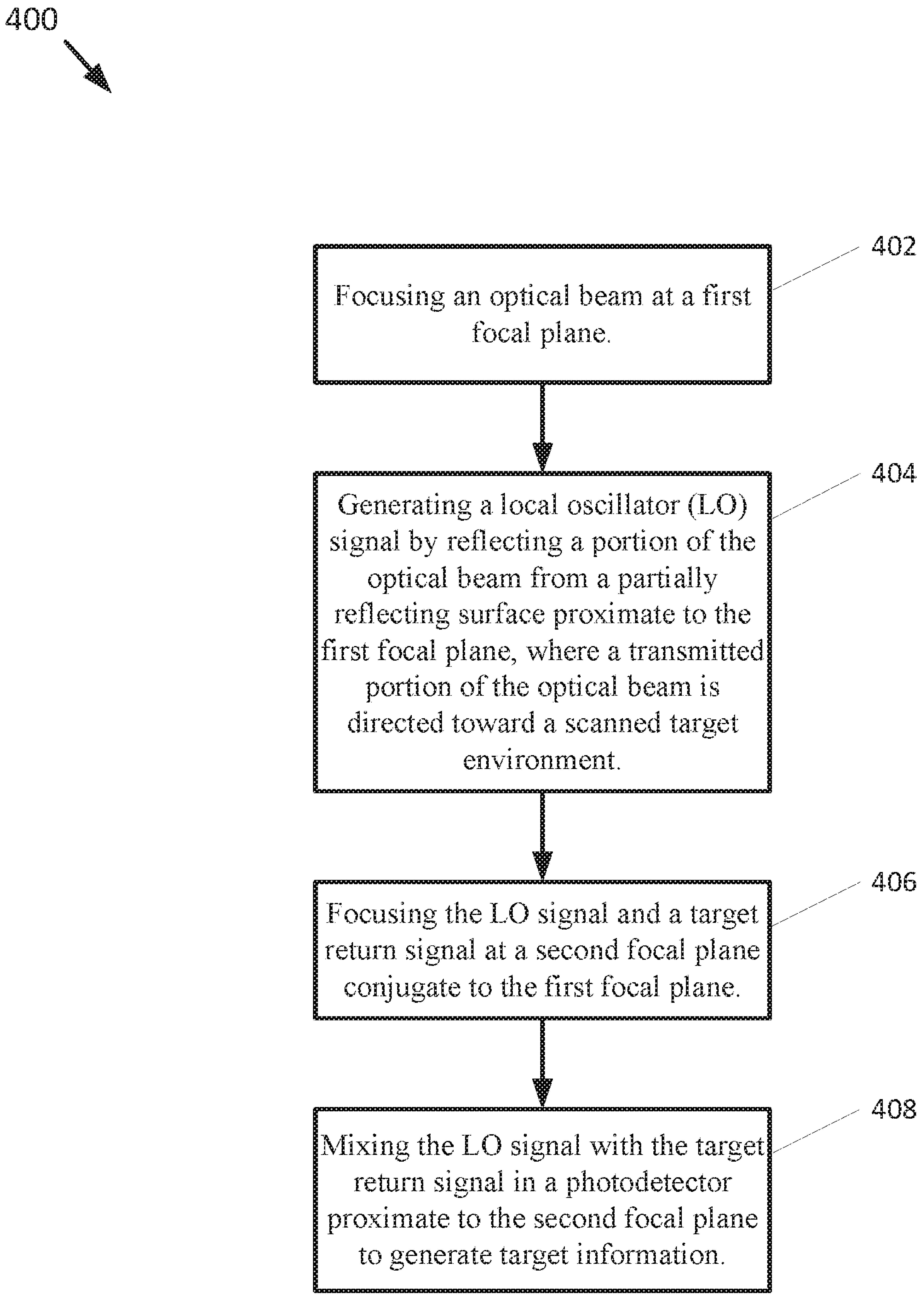

400
402
Focusing an optical beam at a first focal plane.
404
Generating a local oscillator (LO) signal by reflecting a portion of the optical beam from a partially reflecting surface proximate to the first focal plane, where a transmitted portion of the optical beam is directed toward a scanned target environment.
406
Focusing the LO signal and a target return signal at a second focal plane conjugate to the first focal plane.
408
Mixing the LO signal with the target return signal in a photodetector proximate to the second focal plane to generate target information.

FIG. 13

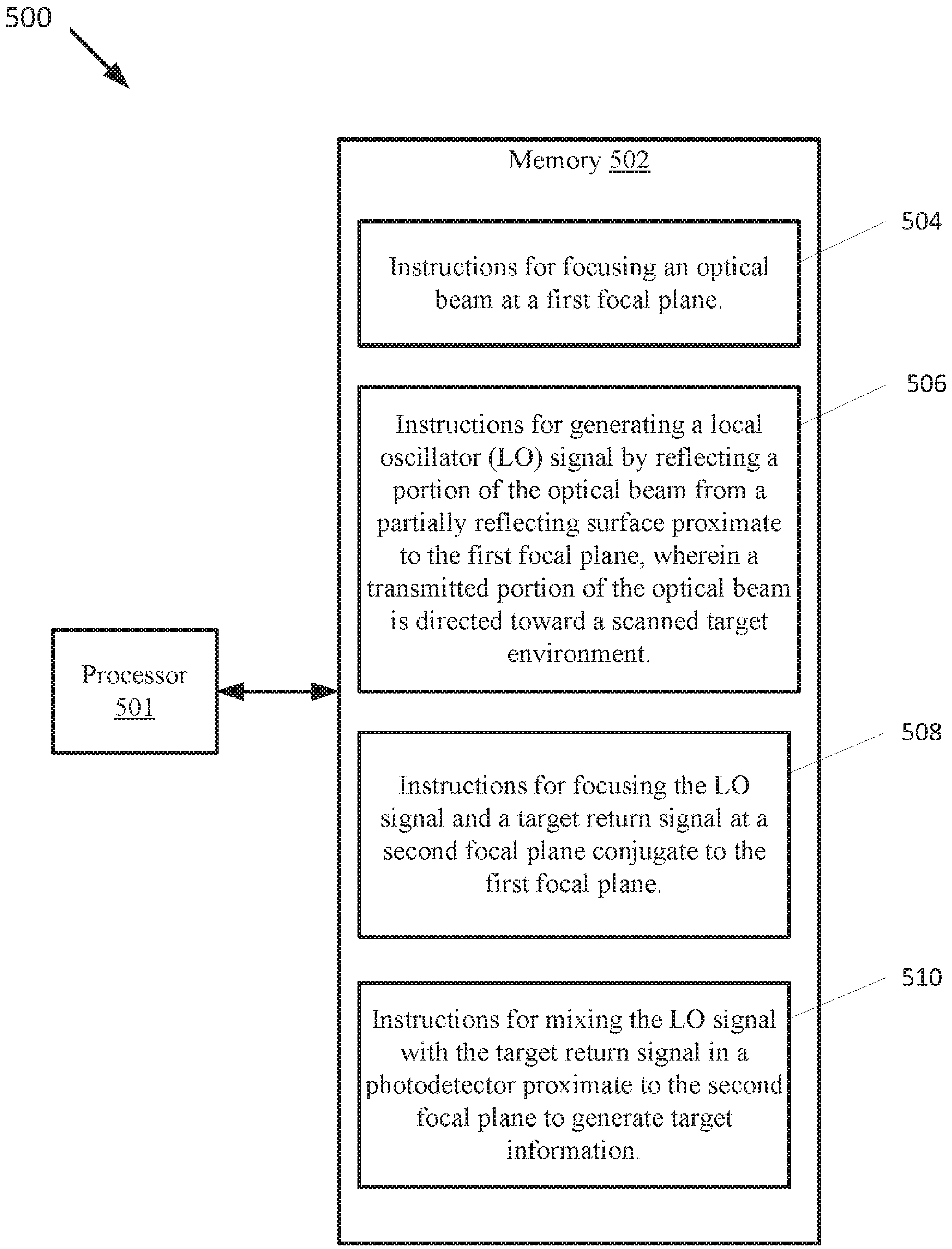
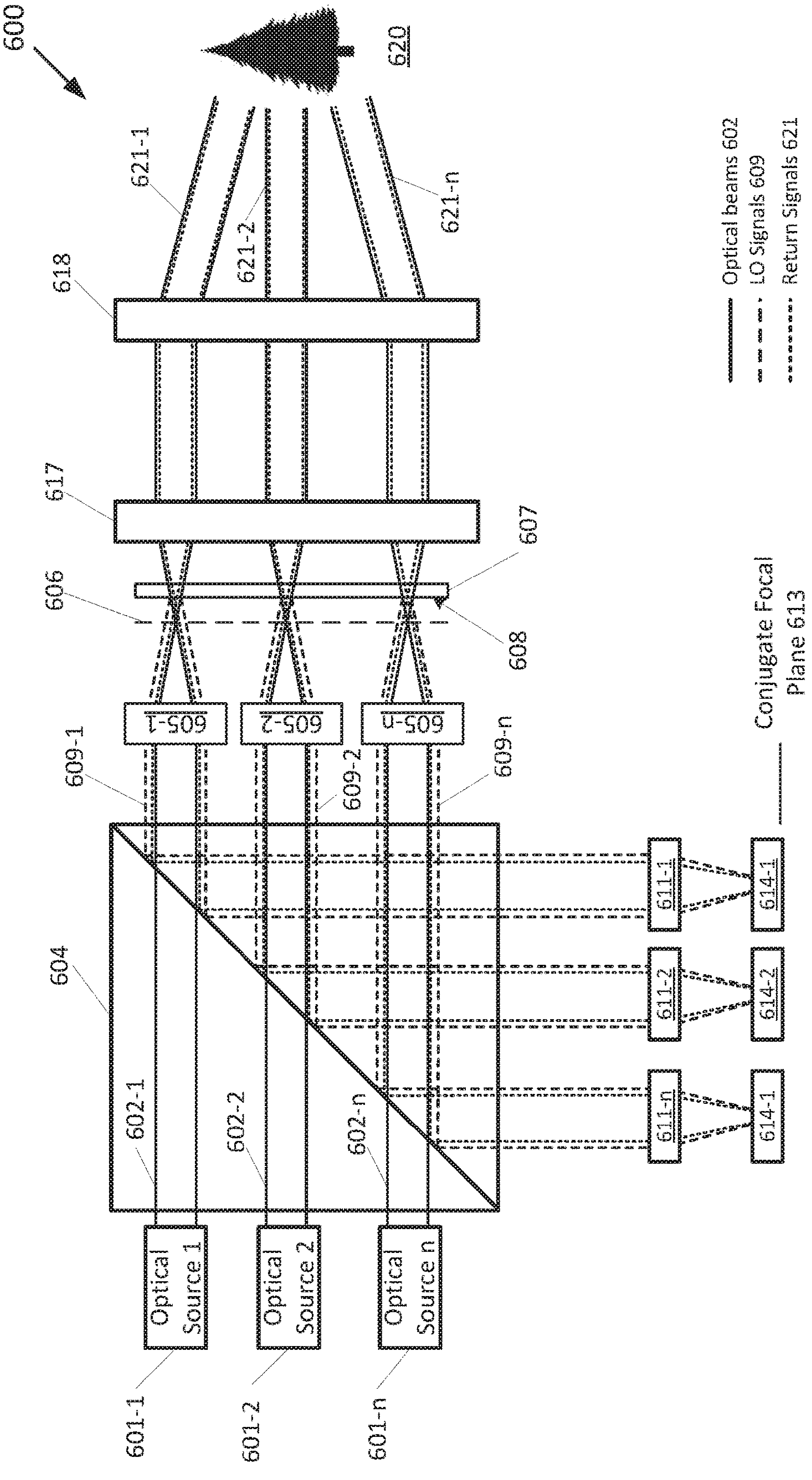

500
Memory 502
504
Instructions for focusing an optical beam at a first focal plane.
506
Instructions for generating a local oscillator (LO) signal by reflecting a portion of the optical beam from a partially reflecting surface proximate to the first focal plane, wherein a transmitted portion of the optical beam is directed toward a scanned target environment.
Processor 501
508
Instructions for focusing the LO signal and a target return signal at a second focal plane conjugate to the first focal plane.
510
Instructions for mixing the LO signal with the target return signal in a photodetector proximate to the second focal plane to generate target information.

FIG. 14


600
620
621-1
621-2
621-n
618
617
607
606
608
605-1
605-2
605-n
609-1
609-2
609-n
604
602-1
602-2
602-n
Optical Source 1
Optical Source 2
Optical Source n
601-1
601-2
601-n
611-1
611-2
611-n
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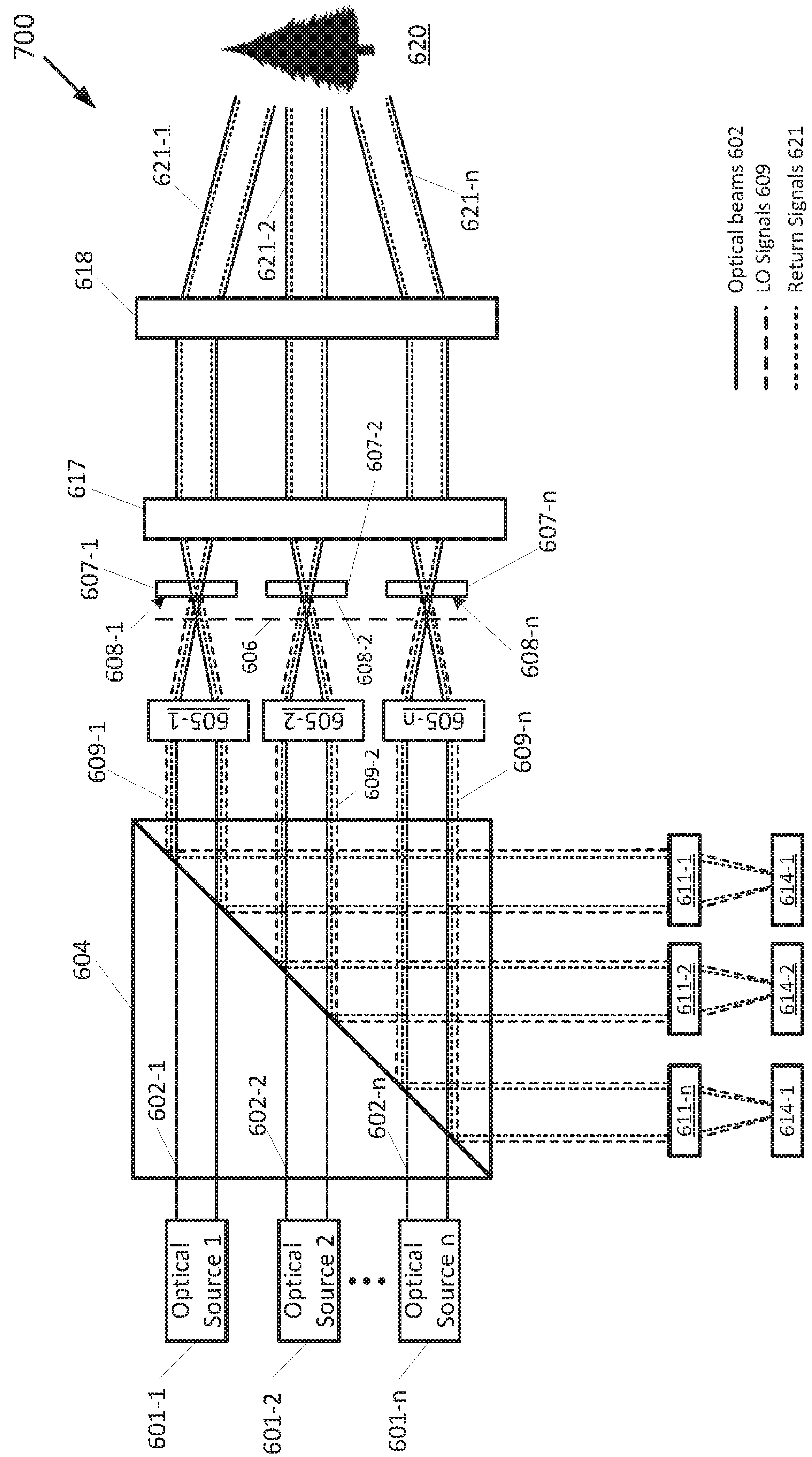
614-2
614-1
Conjugate Focal Plane 613
Optical beams 602
LO Signals 609
Return Signals 621

FIG. 15


700
620
621-1
621-2
621-n
618
617
607-1
607-2
607-n
608-1
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608-2
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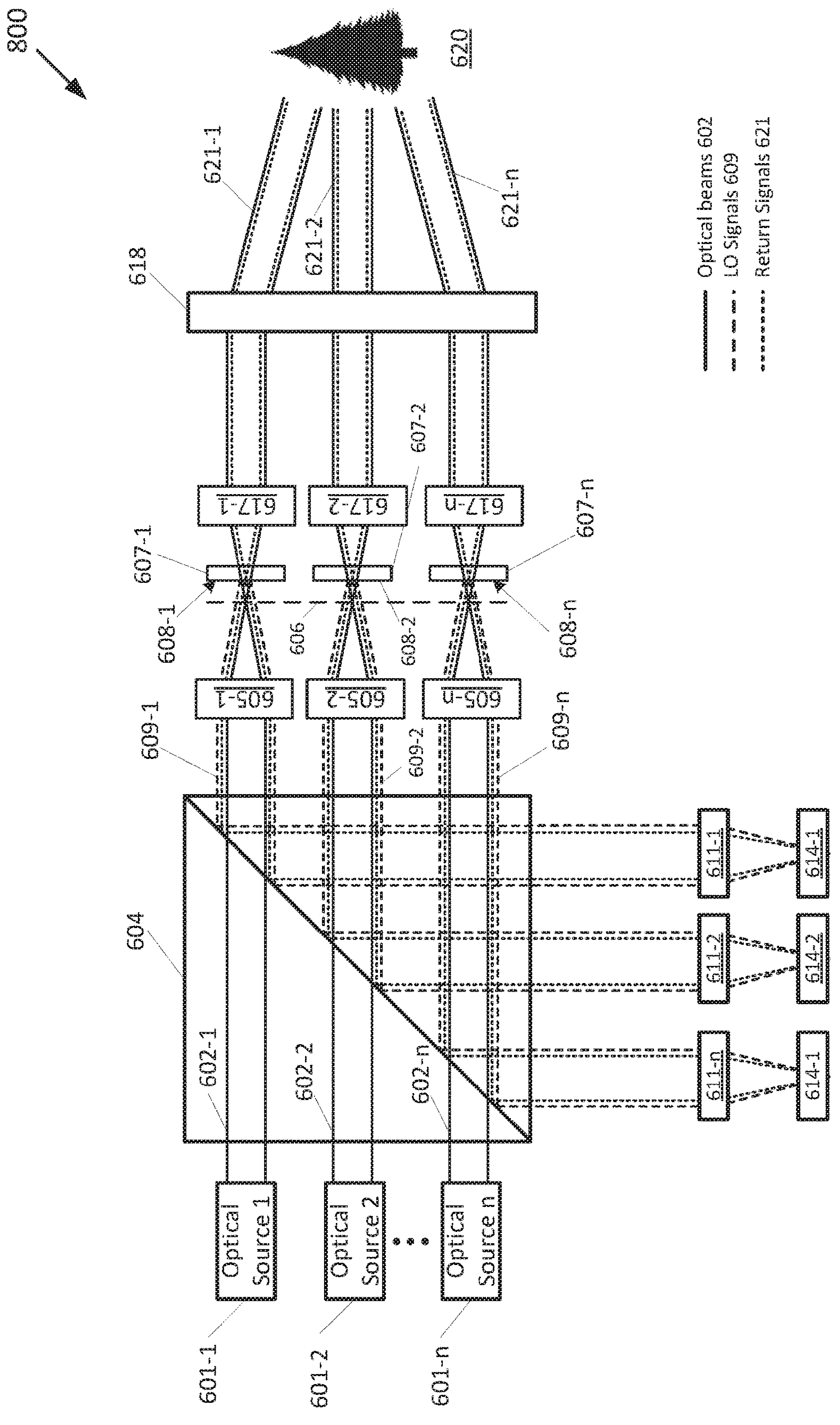
605-2
605-n
609-1
609-2
609-n
604
602-1
602-2
602-n
611-1
611-2
611-n
614-1
614-2
614-1
Optical Source 1
Optical Source 2
Optical Source n
601-1
601-2
601-n
Optical beams 602
LO Signals 609
Return Signals 621

FIG. 16


800
620
621-1
621-2
621-n
618
Optical beams 602
LO Signals 609
Return Signals 621
607-2
617-1
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617-n
607-1
607-n
608-1
606
608-2
608-n
605-1
605-2
605-n
609-1
609-2
609-n
604
602-1
602-2
602-n
611-1
614-1
611-2
614-2
611-n
614-1
Optical Source 1
Optical Source 2
Optical Source n
601-1
601-2
601-n

FIG. 17

COAXIAL LOCAL OSCILLATOR GENERATION AT A CONJUGATE FOCAL PLANE IN AN FMCW LIDAR SYSTEM

FIELD

The present disclosure is related to light detection and ranging (LIDAR) systems in general, and more particularly to the generation of a coaxial local oscillator (LO) signal at a conjugate focal plane with free-space optics.

BACKGROUND

Frequency-Modulated Continuous-Wave (FMCW) LIDAR systems use tunable lasers for frequency-chirped illumination of targets, and coherent receivers for detection of backscattered or reflected light from the targets that are combined with a local copy of the transmitted signal (LO signal). Mixing the LO signal with the return signal, delayed by the round-trip time to the target and back, generates a beat frequency at the receiver that is proportional to the distance to each target in the field of view of the system.

These LIDAR systems employ optical scanners with high-speed mirrors to scan a field of view (FOV) and to de-scan target return signals from the FOV. As mirror speeds are increased, mirror movement during the round trip time to and from a target can cause spatial misalignment between the LO signal and the target return signal, in turn, reduces the spatial mixing efficiency in the photodetectors that are used to mix the signals.

SUMMARY

The present disclosure describes various examples of LIDAR systems and methods for generating coaxial LO and target return signals for improved spatial mixing efficiency.

In one example, a LIDAR system according to the present disclosure includes an optical source to emit an optical beam and free-space optics coupled with the optical source to focus the optical beam at a first focal plane. A local oscillator (LO) signal is generated from a partial reflection of the optical beam from a partially-reflecting surface proximate to the first focal plane, and a transmitted portion of the optical beam is directed toward a scanned target environment. The free-space optics focus the LO signal and a target return signal at a second focal plane, which is a conjugate focal plane to the first focal plane. The system also includes a photodetector with a photosensitive surface proximate to the conjugate focal plane to mix the LO signal with the target return signal to generate target information.

In one example, the free-space optics include a polarization beam splitter (PBS) to transmit the optical beam to a first lens system, where the first lens system focuses the optical beam at the first focal plane. The free-space optics also include an optical window containing the partially reflecting surface where the LO signal is generated from the optical beam and reflected back through the first lens system.

In one example, the free-space optics include a second lens system, where the LO signal is directed through the second lens system by the PBS, and where the second lens system focuses the LO signal and the target return signal at the second focal plane.

In one example, the free-space optics include a third lens system to collimate the transmitted portion of the optical beam and an optical scanner to scan the target environment with the transmitted portion of the optical beam and to de-scan the target return signal. The third lens system focuses the target return signal at the first focal plane, the first lens system collimates the LO signal and the target return signal, and the PBS directs the LO signal and the target return signal to the second lens system.

In one example, the partially reflecting surface is displaced from the first focal plane.

In one example, the photodetector is displaced from the second focal plane.

In one example, a method in a LIDAR system according to the present disclosure includes focusing an optical beam at a first focal plane; generating a local oscillator (LO) signal by reflecting a portion of the optical beam from a partially reflecting surface proximate to the first focal plane, where a transmitted portion of the optical beam is directed toward a scanned target environment; focusing the LO signal and a target return signal at a second focal plane conjugate to the first focal plane; and mixing the LO signal with the target return signal in a photodetector proximate to the second focal plane to generate target information.

In one example, the method includes generating the optical beam with a coherent optical source; transmitting the optical beam through a polarization beam splitter (PBS) and through a first lens system to focus the optical beam at the first focal plane and through an optical window containing the partially reflecting surface, where the LO signal is reflected back through the first lens system.

In one example, the method includes reflecting the LO signal and the target return signal from the PBS through a second lens system, where the LO signal and the target return signal are focused at the second focal point.

In one example, the method includes collimating the transmitted portion of the optical beam with a third lens system, scanning the target environment with the transmitted portion of the optical beam, de-scanning the target return signal, and focusing the target return signal at the first focal plane with the third lens system.

In one example, the method includes collimating the LO signal and the target return signal with the first lens system and directing the LO signal and the target return signal to the second lens system with the PBS, where the LO signal and the target return signal are focused at the second focal plane.

In one example of the method, the partially reflecting surface of the optical window is displaced from the first focal plane.

In one example of the method, the photodetector is displaced from the second focal plane.

In one example, a LIDAR system according to the present disclosure includes a processor and a non-transitory computer-readable medium storing instructions, that when executed by the processor, cause the LIDAR system to perform operations, the operations including focusing an optical beam at a first focal plane; generating a local oscillator (LO) signal by reflecting a portion of the optical beam from a partially reflecting surface proximate to the first focal plane, where a transmitted portion of the optical beam is directed toward a scanned target environment; focusing the LO signal and a target return signal at a second focal plane conjugate to the first focal plane; and mixing the LO signal with the target return signal in a photodetector proximate to the second focal plane to generate target information.

In one example, the operations also include generating the optical beam with a coherent optical source and transmitting the optical beam through a polarization beam splitter (PBS) and through a first lens system to focus the optical beam at the first focal plane, and through an optical window including the partially reflecting surface, where the LO signal is reflected back through the first lens system.

In one example, the operations also include reflecting the LO signal and the target return signal from the PBS through a second lens system, where the LO signal and the target return signal are focused at the second focal point.

In one example, the operations also include collimating the transmitted portion of the optical beam with a third lens system; scanning the target environment with the transmitted portion of the optical beam; de-scanning the target return signal; and focusing the target return signal at the first focal plane with the third lens system.

In one example, the operations also include collimating the LO signal and the target return signal with the first lens system and directing the LO signal and the target return signal to the second lens system with the PBS, where the LO signal and the target return signal are focused at the second focal plane.

In one example, the partially reflecting surface of the optical window is displaced from the first focal plane.

In one example, the photodetector is displaced from the second focal plane.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the various examples, reference is now made to the following detailed description taken in connection with the accompanying drawings in which like identifiers correspond to like elements:

FIG. **1** illustrates an example FMCW LIDAR system according to embodiments of the present disclosure;

FIG. **2** is a time-frequency diagram illustrating an example of FMCW LIDAR waveforms according to embodiments of the present disclosure;

FIG. **3** is a block diagram of an example optical system according to embodiments of the present disclosure;

FIG. **4** is a block diagram of an example optical system according to embodiments of the present disclosure;

FIG. **5** is a block diagram of an example optical system according to embodiments of the present disclosure;

FIG. **6** is a block diagram of an example optical system according to embodiments of the present disclosure;

FIG. **7** is a block diagram of an example optical system according to embodiments of the present disclosure;

FIG. **8** is a block diagram of an example optical system according to embodiments of the present disclosure;

FIG. **9** is a block diagram of an example optical system according to embodiments of the present disclosure;

FIG. **10** is a block diagram of an example optical system according to embodiments of the present disclosure;

FIG. **11** is an example of a system of lenses according to embodiments of the present disclosure;

FIG. **12** is a block diagram of an example optical system according to embodiments of the present disclosure;

FIG. **13** is a flowchart illustrating an example method for generating a coaxial local oscillator at a conjugate focal plane according to embodiments of the present disclosure;

FIG. **14** is a block diagram of an example system for generating a coaxial local oscillator at a conjugate focal plane according to embodiments of the present disclosure;

FIG. **15** is a block diagram of an example multi-beam optical system according to embodiments of the present disclosure;

FIG. **16** is a block diagram of an example multi-beam optical system according to embodiments of the present disclosure; and

FIG. **17** is a block diagram of an example multi-beam optical system according to embodiments of the present disclosure.

DETAILED DESCRIPTION

The present disclosure describes various examples of LIDAR systems and methods for detecting and mitigating the effects of obstructions on LIDAR windows. According to some embodiments, the described LIDAR system may be implemented in any sensing market, such as, but not limited to, transportation, manufacturing, metrology, medical, and security systems. According to some embodiments, the described LIDAR system is implemented as part of a front-end of frequency modulated continuous-wave (FMCW) device that assists with spatial awareness for automated driver assist systems, or self-driving vehicles.

FIG. **1** illustrates a LIDAR system **100** according to example implementations of the present disclosure. The LIDAR system **100** includes one or more of each of a number of components, but may include fewer or additional components than shown in FIG. **1**. As shown, the LIDAR system **100** includes optical circuits **101** implemented on a photonics chip. The optical circuits **101** may include a combination of active optical components and passive optical components. Active optical components may generate, amplify, and/or detect optical signals and the like. In some examples, the active optical component includes optical beams at different wavelengths, and includes one or more optical amplifiers, one or more optical detectors, or the like.

Free space optics **115** may include one or more optical waveguides to carry optical signals, and route and manipulate optical signals to appropriate input/output ports of the active optical circuit. The free space optics **115** may also include one or more optical components such as taps, wavelength division multiplexers (WDM), splitters/combiners, polarization beam splitters (PBS), collimators, couplers or the like. In some examples, the free space optics **115** may include components to transform the polarization state and direct received polarized light to optical detectors using a PBS, for example. The free space optics **115** may further include a diffractive element to deflect optical beams having different frequencies at different angles along an axis (e.g., a fast-axis).

In some examples, the LIDAR system **100** includes an optical scanner **102** that includes one or more scanning mirrors that are rotatable along an axis (e.g., a slow-axis) that is orthogonal or substantially orthogonal to the fast-axis of the diffractive element to steer optical signals to scan an environment according to a scanning pattern. For instance, the scanning mirrors may be rotatable by one or more galvanometers. The optical scanner **102** also collects light incident upon any objects in the environment into a return optical beam that is returned to the passive optical circuit component of the optical circuits **101**. For example, the return optical beam may be directed to an optical detector by a polarization beam splitter. In addition to the mirrors and galvanometers, the optical scanner **102** may include components such as a quarter-wave plate, lens, anti-reflective coated window or the like.

To control and support the optical circuits **101** and optical scanner **102**, the LIDAR system **100** includes LIDAR control systems **110**. The LIDAR control systems **110** may include a processing device for the LIDAR system **100**. In some examples, the processing device may be one or more general-purpose processing devices such as a microprocessor, central processing unit, or the like. More particularly, the processing device may be complex instruction set computing (CISC) microprocessor, reduced instruction set computer (RISC) microprocessor, very long instruction word (VLIW) microprocessor, or processor implementing other instruction sets, or processors implementing a combination of instruction sets. The processing device may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like.

In some examples, the LIDAR control systems **110** may include a signal processing unit **112** such as a digital signal processor (DSP). The LIDAR control systems **110** are configured to output digital control signals to control optical drivers **103**. In some examples, the digital control signals may be converted to analog signals through signal conversion unit **106**. For example, the signal conversion unit **106** may include a digital-to-analog converter. The optical drivers **103** may then provide drive signals to active optical components of optical circuits **101** to drive optical sources such as lasers and amplifiers. In some examples, several optical drivers **103** and signal conversion units **106** may be provided to drive multiple optical sources.

The LIDAR control systems **110** are also configured to output digital control signals for the optical scanner **102**. A motion control system **105** may control the galvanometers of the optical scanner **102** based on control signals received from the LIDAR control systems **110**. For example, a digital-to-analog converter may convert coordinate routing information from the LIDAR control systems **110** to signals interpretable by the galvanometers in the optical scanner **102**. In some examples, a motion control system **105** may also return information to the LIDAR control systems **110** about the position or operation of components of the optical scanner **102**. For example, an analog-to-digital converter may in turn convert information about the galvanometers' position to a signal interpretable by the LIDAR control systems **110**.

The LIDAR control systems **110** are further configured to analyze incoming digital signals. In this regard, the LIDAR system **100** includes optical receivers **104** to measure one or more beams received by optical circuits **101**. For example, a reference beam receiver may measure the amplitude of a reference beam from the active optical component, and an analog-to-digital converter converts signals from the reference receiver to signals interpretable by the LIDAR control systems **110**. Target receivers measure the optical signal that carries information about the range and velocity of a target in the form of a beat frequency, modulated optical signal. The reflected beam may be mixed with a second signal from a local oscillator. The optical receivers **104** may include a high-speed analog-to-digital converter to convert signals from the target receiver to signals interpretable by the LIDAR control systems **110**. In some examples, the signals from the optical receivers **104** may be subject to signal conditioning by signal conditioning unit **107** prior to receipt by the LIDAR control systems **110**. For example, the signals from the optical receivers **104** may be provided to an operational amplifier for amplification of the received signals and the amplified signals may be provided to the LIDAR control systems **110**.

In some applications, the LIDAR system **100** may additionally include one or more imaging devices **108** configured to capture images of the environment, a global positioning system **109** configured to provide a geographic location of the system, or other sensor inputs. The LIDAR system **100** may also include an image processing system **114**. The image processing system **114** can be configured to receive the images and geographic location, and send the images and location or information related thereto to the LIDAR control systems **110** or other systems connected to the LIDAR system **100**.

In operation according to some examples, the LIDAR system **100** is configured to use nondegenerate optical sources to simultaneously measure range and velocity across two dimensions. This capability allows for real-time, long range measurements of range, velocity, azimuth, and elevation of the surrounding environment.

In some examples, the scanning process begins with the optical drivers **103** and LIDAR control systems **110**. The LIDAR control systems **110** instruct the optical drivers **103** to independently modulate one or more optical beams, and these modulated signals propagate through the passive optical circuit to the collimator. The collimator directs the light at the optical scanning system that scans the environment over a preprogrammed pattern defined by the motion control system **105**. The optical circuits **101** may also include a polarization wave plate (PWP) to transform the polarization of the light as it leaves the optical circuits **101**. In some examples, the polarization wave plate may be a quarter-wave plate or a half-wave plate or a non-reciprocal polarization rotator such as Faraday rotator. A portion of the polarized light may also be reflected back to the optical circuits **101**. For example, lensing or collimating systems used in LIDAR system **100** may have natural reflective properties or a reflective coating to reflect a portion of the light back to the optical circuits **101**.

Optical signals reflected back from the environment pass through the optical circuits **101** to the receivers. Because the polarization of the light has been transformed, it may be reflected by a polarization beam splitter along with the portion of polarized light that was reflected back to the optical circuits **101**. Accordingly, rather than returning to the same fiber or waveguide as an optical source, the reflected light is reflected to separate optical receivers. These signals interfere with one another and generate a combined signal. Each beam signal that returns from the target produces a time-shifted waveform. The temporal phase difference between the two waveforms generates a beat frequency measured on the optical receivers (photodetectors). The combined signal can then be reflected to the optical receivers **104**.

The analog signals from the optical receivers **104** are converted to digital signals using ADCs. The digital signals are then sent to the LIDAR control systems **110**. A signal processing unit **112** may then receive the digital signals and interpret them. In some embodiments, the signal processing unit **112** also receives position data from the motion control system **105** and galvanometers (not shown) as well as image data from the image processing system **114**. The signal processing unit **112** can then generate a 3D point cloud with information about range and velocity of points in the environment as the optical scanner **102** scans additional points. The signal processing unit **112** can also overlay a 3D point cloud data with the image data to determine velocity and distance of objects in the surrounding area. The system also processes the satellite-based navigation location data to provide a precise global location.

FIG. **2** is a time-frequency diagram **200** of an FMCW scanning signal **201** that can be used by a LIDAR system, such as system **100**, to scan a target environment according to some embodiments. In one example, the scanning waveform **201**, labeled as $f_{FM}(t)$, is a sawtooth waveform (sawtooth "chirp") with a chirp bandwidth Δf_C and a chirp period

T_C. The slope of the sawtooth is given as $k=(\Delta f_C/T_C)$. FIG. **2** also depicts target return signal **202** according to some embodiments. Target return signal **202**, labeled as $f_{FM}(t-\Delta t)$, is a time-delayed version of the scanning signal **201**, where Δt is the round trip time to and from a target illuminated by scanning signal **201**. The round trip time is given as $\Delta t=2R/v$, where R is the target range and v is the velocity of the optical beam, which is the speed of light c. The target range, R, can therefore be calculated as $R=c(\Delta t/2)$. When the return signal **202** is optically mixed with the scanning signal, a range dependent difference frequency ("beat frequency") $\Delta f_R(t)$ is generated. The beat frequency $\Delta f_R(t)$ is linearly related to the time delay Δt by the slope of the sawtooth k. That is, $\Delta f_R(t)=k\Delta t$. Since the target range R is proportional to Δt, the target range R can be calculated as $R=(c/2)(\Delta f_R(t)/k)$. That is, the range R is linearly related to the beat frequency $\Delta f_R(t)$. The beat frequency $\Delta f_R(t)$ can be generated, for example, as an analog signal in optical receivers **104** of system **100**. The beat frequency can then be digitized by an analog-to-digital converter (ADC), for example, in a signal conditioning unit such as signal conditioning unit **107** in LIDAR system **100**. The digitized beat frequency signal can then be digitally processed, for example, in a signal processing unit, such as signal processing unit **112** in system **100**. It should be noted that the target return signal **202** will, in general, also include a frequency offset (Doppler shift) if the target has a velocity relative to the LIDAR system **100**. The Doppler shift can be determined separately, and used to correct the frequency of the return signal, so the Doppler shift is not shown in FIG. **2** for simplicity and ease of explanation. It should also be noted that the sampling frequency of the ADC will determine the highest beat frequency that can be processed by the system without aliasing. In general, the highest frequency that can be processed is one-half of the sampling frequency (i.e., the "Nyquist limit"). In one example, and without limitation, if the sampling frequency of the ADC is 1 gigahertz, then the highest beat frequency that can be processed without aliasing (Δf_{Rmax}) is 500 megahertz. This limit in turn determines the maximum range of the system as $R_{max}=(c/2)(\Delta f_{Rmax}/k)$ which can be adjusted by changing the chirp slope k. In one example, while the data samples from the ADC may be continuous, the subsequent digital processing described below may be partitioned into "time segments" that can be associated with some periodicity in the LIDAR system **100**. In one example, and without limitation, a time segment might correspond to a predetermined number of chirp periods T, or a number of full rotations in azimuth by the optical scanner.

FIG. **3** illustrates a two-dimensional representation of a system of optical components **300** according to various aspects of the present disclosure. System **300** may include one or more components of optical circuits **101**, free-space optics **115** and optical scanner **102** in system **100** as illustrated in FIG. **1**

System **300** includes an optical source **301** that generates a coherent optical beam **302** with a selected polarization (e.g., s-polarization or p-polarization). As illustrated by section A-A (**303**), the optical beam **302** has an approximately circular or elliptical cross-section. The optical source **301** directs the optical beam **302** to a polarization beam splitter (PBS) **304** that transmits the selected polarization of the optical beam **302** to a first lens system **305**. According to some embodiments, a polarizing wave-plate or a Faraday rotator can be used to alter reflected polarizations from optical window **307**. According to some embodiments, optical window **307** includes a wedge glass that is configured to eliminate spatial interference between front and back surface reflections. In some scenarios, optical window **307** can be configured based on a scan speed and/or range of interest. In this fashion, wedge orientation can induce a shift in LO signal on one or more photodetectors, which can be used to compensate for the overlap mismatch between return signal and LO signal due to descanning lag in fast unidirectional scanners such as spinning polygon.

According to some embodiments, a beam splitter (BS) may be used in place of PBS **304**. The first lens system **305** is configured to focus the optical beam **302** at a first focal plane **306**. Lens system can be a single aspheric lens or a multi-element lens design which includes any combination of spherical and aspherical surfaces.

An optical window **307** has a partially-reflecting surface **308** located at the first focal plane **306**. The partially-reflecting surface **308** reflects a portion of the optical beam **302** back toward the first lens system **305** as a local oscillator (LO) signal **309** with an altered polarization. The optical window **307** is substantially perpendicular to the primary optical axis **310** of the first lens system **305**, so the return path of the LO signal **309** is substantially the same as the forward path of the optical beam **302**. Although not depicted, the back surface of the optical window **307** may include a partially-reflecting surface. Therefore, an additional LO signal may be reflected from the optical beam **302** at the back surface of the optical window **307**. In one embodiment, either the LO signal **309** from the front surface or the additional LO signal from the back surface may be used as the LO signal. However, of the two LO signal, one may be in-focus while the other may be out-of-focus resulting in competing LO signals and increased shot noise. Therefore, in some embodiments, the optical window **307** may be a wedge glass such that the LO signal reflected from the back surface of the optical window **307** does not interfere with the front surface reflection (e.g., LO signal **309**) or vice versa.

The LO signal **309** is collimated by the first lens system **305** and directed to the PBS **304** where the altered polarization of the LO signal **309** is reflected by the PBS **304** to a second lens system **311**. As illustrated by section B-B **312**, the LO signal **309** has an approximately circular or elliptical cross-section, the same or similar to section A-A **303**. The second lens system **311** focuses the LO signal **309** at a second focal plane **313** that is a conjugate focal plane to the first focal plane **306**. A photodetector **314** with a photosensitive surface located at the second focal plane **313** receives the energy of the LO signal **309**. Ideally, the LO signal **309** would be focused to a point on the second focal plane **313**, but practical limitations on the alignment of the optical components could result in a measure of defocusing as illustrated by the projection **316** of the LO signal **309** onto the surface of the detector **315**, which has a non-zero diameter. Additional optical components of system **300**, including a third lens system **317** and an optical scanner **318** are described below.

FIG. **4** illustrates the full path of the optical beam **302** to a target environment **320**, in isolation, according to some embodiments. After converging at the first focal plane **306**, the portion of the optical beam **302** not reflected from the optical window **307** diverges toward the third lens system **317**. In one example, the third lens system **317** has the same focal length as the first lens system **305**, so that the optical beam **302** is collimated by the third lens system **317**. As illustrated by section C-C **319** in FIG. **4**, the collimated optical beam **302** has an approximately circular cross-section.

The collimated optical beam **302** is received by the optical scanner **318**, which scans the target environment **320** in azimuth and elevation directions. Objects in the target environment **320** reflect a portion of the optical beam **302** as a return signal as illustrated in FIG. **5**. In FIG. **5**, a return signal **321**, with an altered polarization from the optical beam **302**, is de-scanned by the optical scanner **318**. Ignoring any effects from de-scanning errors in the optical scanner **318** (described in more detail below), the de-scanned return signal **321** is a collimated beam with an approximately circular cross-section as illustrated by section D-D **322** in FIG. **5**, which is substantially parallel to the principal optical axis **310** of the third lens system **317** and the first lens system **305**. Accordingly, the return signal **321** converges at the first focal plane **306** and then diverges toward the first lens system **305**, where it is re-collimated. The re-collimated return signal **321** is reflected by the PBS **304**, due to its altered polarization, and directed toward the second lens system **311**.

The second lens system **311** focuses the return signal **321** at the second focal plane **313**, as described above with respect to the LO signal **309**. According to some embodiments, the return signal **321** can be focused to a point on the second focal plane **313**.

FIG. **6** illustrates the operation of system **300** when all of the optical components are aligned in a manner that minimizes the optical aberrations. In one example, the optical beam, LO signal and return signal (e.g., optical beam **302**, LO signal **309**, and return signal **321** of FIGS. **3** and **4**) would all be symmetrically aligned. This alignment is illustrated in FIG. **6** through the use of compound beam notation. For example, the beam **322** between the first focal plane **306** and the target environment **320** includes both the outgoing optical beam **302** and the incoming return signal **321**; the beam **323** between the first focal point **306** and the PBS **304** includes the outgoing optical beam **302**, the incoming return signal (e.g., return signal **321** as depicted in FIG. **5**), and the LO signal (e.g., LO signal **309** of FIG. **3**); and the beam **324** between the PBS **304** and the photodetector **314** includes both the LO signal (e.g., LO signal **309** of FIG. **3**) and the return signal (e.g., return signal **321** of FIG. **5**). In this example of system **300**, the LO signal and return signal (e.g., LO signal **309** and the return signal **321** of FIGS. **3** and **5**) would be focused at a point on the second focal plane **313**.

FIG. **7** illustrates a system where the optical window **307** has been misaligned by the angle ϕ. A misalignment may cause the point focus of the LO signal **309** to diverge from the point focus of the return signal **321** on the second focal plane **313**. The spatial mixing efficiency (γ) of the system **300** is a function of the overlap integral of the spot size of the LO signal **309** and the spot size of the return signal **321**, given by:

$$\gamma \propto \frac{\left| \int\int_{-det}^{det} E_{LO}(x, y) * E_s(x - x_0, y - y_0) dxdy \right|^2}{\int\int_{-det}^{det} |E_{LO}(x, y)|^2 \cdot \int\int_{-det}^{det} |E_s(x - x_0, y - y_0)|^2}$$

where E_s, and E_{lo} are the return signal and LO signal electric field profiles on the photodetector, x_0 and y_0 are the displacement of the return signal spot relative to the LO signal spot, and det is the radius of detector **314** for a circular detector. If the LO signal spot and the return signal spot do not overlap, as illustrated in FIG. **7**, the spatial mixing efficiency will be reduced to zero.

Mixing efficiency can be maximized, even if a misalignment of the optical window **307** occurs, by locating the surface **315** of the photodetector **314** in front of the second focal plane **313** (or behind the second focal plane **313** to achieve a similar de-focusing effect) as illustrated in FIG. **8**, where the projection of the compound beam **324** on the surface **315** of the photodetector **314** (which includes the coaxial LO signal **309** and return signal **321**) has an increased diameter compared with the spot focus of the compound beam **324** in the configuration of FIG. **6**.

FIG. **9** illustrates the effect of repositioning the photodetector **314** in front of the second focal plane **313** where the LO signal **309** and the return signal **321** are misaligned. Rather than two non-overlapping focal points, the LO signal **309** and the return signal **321** have overlapping areas on the face **315** of the photodetector **314**, where spatial mixing can occur to generate the baseband signal $\Delta f_R(t)$.

Positioning the photodetector **314** in front of the second focal plane **313** may also increase the spatial mixing to combat misalignment between the LO signal **309** and the return signal **321** due to de-scanning lag of return signal **321** in the optical scanner **318** caused by potential. At angular velocities greater than approximately 20,000 degrees per second, the time delay for return signals, from targets at sufficiently long range, is long enough that the scanning mirror in the optical scanner **318** has time to rotate a non-negligible angle, causing a skew in the angle of the return signal **321** that is reflected to the third lens system **317** by the optical scanner **318**.

This skewing effect is illustrated in the example of FIG. **10**, where the return signal **321** is skewed from the optical beam **302** as shown in section G-G. The skew angle is propagated through the combination of the third lens system **317** and the first lens system **305** as illustrated in FIG. **11**, where the lens systems are represented by equivalent, thin double-convex lenses. If the return signal **321** enters the third lens system **317** as a plane wave at an angle θ with respect to the principal optical axis **310**, then the return signal **321** will converge at the first focal plane **306** at a point determined by the focal length of the third lens system **317** and the angle θ. Additionally, as noted previously, since the distance between first and third lens system is equal to the sum of their focal lengths, the return signal **321** will be re-collimated by the first lens system **305** at the angle θ with respect to the principal optical axis **310**.

Returning to FIG. **10**, the skewed return signal **321** and the LO signal **309** are reflected by the PBS **304** and directed to the second lens system **311** as overlapping signals as illustrated by section H-H. Both signals are focused at the second focal plane **313**, but at different points. The non-skewed LO signal **309** will be focused on the principal optical axis of the second lens system **311**, while the skewed return signal **321** will be focused at a point offset from the principal optical axis, just as the third lens system **317** focused the return signal **321** on the first local plane **306**. However, since the photodetector **314** is located in front of the second focal plane **313**, there is substantial overlap between the LO signal **309** and the return signal **321** on the face **315** of the photodetector **314**.

FIG. **12** illustrates the example system **300** with a modification that generates a complete overlap between the LO signal **309** and the return signal **321** on the surface **315** of the photodetector **314**. The modification comprises a displacement of the partially-reflecting surface **308** of the optical window **307** by moving the optical window away from the first focal plane **306** by a distance δ toward the third lens system **317** in the example of FIG. **12**. It should be noted that the same effect can be achieved by moving the optical window away from the focal plane **306** in the opposite direction, toward the first lens system **305**. This displacement causes the optical beam **302** to be reflected from the partially-reflecting surface **308** after it has diverged from its focal point. As a result, the LO signal **309** reflected from the partially-reflecting surface **308** has a substantially greater diameter than it would have if reflected at the focal plane **306**, as illustrated by section J-J.

As illustrated in FIG. **12**, the second lens system **311** focuses the LO signal **309** and the return signal **321** toward the second focal plane **313**. The location of the photodetector **314** and the increased diameter of the LO signal **309** result in a complete overlap of the LO signal **309** and the return signal **321** to maximize the spatial mixing efficiency.

FIG. **13** is a flowchart illustrating an example method **400** in a LIDAR system for generating a coaxial local oscillator signal at a conjugate focal plane according to embodiments of the present disclosure. Method **400** begins at operation **402**, focusing an optical beam (e.g., optical beam **302**) at a first focal plane (e.g., focal plane **306**). Method **400** continues at operation **404**, generating a local oscillator (LO) signal (e.g., LO signal **309**) by reflecting a portion of the optical beam from a partially reflecting surface (e.g., surface **308** on optical window **307**) proximate to the first focal plane, where a transmitted portion of the optical beam is directed toward a scanned target environment (e.g., by optical scanner **318**). Next, method **400** continues at operation **406**, focusing the LO signal and a target return signal (e.g., return signal **321**) at a second focal plane (e.g., second focal plane **313**) conjugate to the first focal plane. Method **400** concludes with operation **408**, mixing the LO signal with the target return signal in a photodetector (e.g., photodetector **314**) proximate to the second focal plane to generate target information.

FIG. **14** is a block diagram illustrating an example processing system **500** in a LIDAR system for generating a coaxial local oscillator signal at a conjugate focal plane according to embodiments of the present disclosure. Processing system **500** includes a processor **501**. In one example, processor **501** may be embedded in the signal processing unit **112** in the LIDAR control systems **110** in LIDAR system **100**. In some examples, **501** may be one or more general-purpose processing devices such as a microprocessor, central processing unit, or the like. More particularly, processor **501** may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computer (RISC) microprocessor, very long instruction word (VLIW) microprocessor, or processor implementing other instruction sets, or processors implementing a combination of instruction sets. The processor **501** may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like.

Processing system **500** also includes a computer-readable memory **502** coupled to the processor **501**. Memory **502** may be, for example, read-only memory (ROM), random-access memory (RAM, programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), flash memory, magnetic disk memory such hard disk drives (HDD), optical disk memory such as compact-disk read-only (CD-ROM) and compact disk read-write memory (CD-RW), or any other type of non-transitory memory.

In some examples, memory **502** includes instructions that, when executed by the processor **501**, cause a LIDAR system (e.g., LIDAR system **100**) to generate a coaxial local oscillator signal (e.g., LO signal **309**) at a conjugate focal plane (e.g., second focal plane **313**) according to embodiments of the present disclosure.

In one example, memory **502** includes instructions **504** for focusing an optical beam (e.g., optical beam **302**) at a first focal plane (e.g., focal plane **306**); instructions **506** for generating a local oscillator (LO) signal (e.g., LO signal **309**) by reflecting a portion of the optical beam from a partially reflecting surface (e.g., surface **308** of optical window **307**) proximate to the first focal plane, where a transmitted portion of the optical beam is directed toward a scanned target environment (e.g., by optical scanner **318**); instructions **508** for focusing the LO signal and a target return signal (e.g., return signal **321**) at a second focal plane conjugate to the first focal plane (e.g., second focal plane **313**); and instructions **510** for mixing the LO signal with the target return signal in a photodetector (e.g., photodetector **314**) proximate to the second focal plane to generate target information.

FIG. **15** is a block diagram of an example multi-beam LIDAR system **600** for generating coaxial local oscillator signals at a conjugate plane according to embodiments of the present disclosure. System **600** is functionally similar to system **300**, which has already been described in detail, except that system **600** includes multiple FMCW optical sources **601-1** through **601-*n***, where each optical source may operate at a different frequency and/or bandwidth and emit a corresponding optical beams **602-1** through **602-*n*** (collectively, optical beams **602**). Each of the optical beams **602** is passed by a polarization beam splitter (PBS) **604** to a corresponding first lens system **605-1** through **605-*n*** (collectively, first lens systems **605**). Each first lens system **605** focuses its corresponding optical beam **602** to a focal point on a first focal plane **606**. The optical beams **602** then diverge beyond the first focal plane **606**, where they are partially reflected by a partially-reflecting surface **608** on an optical window **607**. The reflected portion of each optical beam **602** comprises a corresponding local oscillator (LO) signal **609-1** through **609-*n*** (collectively, LO signals **609**).

The LO signals **609** are each collimated by their respective first lens system **605** and then reflected by PBS **604** toward corresponding second lens system **611-1** through **611-*n*** (collectively, second lens systems **611**). Each second lens system **611** focuses its corresponding LO signal **609** to a focal point on a second focal plane **613** that is conjugate to the first focal plane **606**. Each LO signal **609** is intercepted by a corresponding photodetector **611-1** through **611-*n*** (collectively, photodetectors **611**) such that each photodetector **611** is illuminated by a corresponding LO signal **609** with a non-zero diameter.

The portion of each optical beam **602** that is not reflected from optical window **606** is collimated by a third lens system **618** and transmitted to an optical scanner **618**. Optical scanner **618** scans a target environment **620** with the optical beams **602**, and de-scans corresponding target return signals **621-1** through **621-*n*** (collectively, return signals **621**). The return signals **621** are focused by third lens system **617** at the first focal plane **606** and then diverge to intercept the corresponding first lens system **605**. Each first lens system **605** collimates its corresponding return signal **621**, which are then reflected by PBS **604** toward second lens systems **611**. Each second lens system **611** focuses its corresponding return signal **621** on the second focal plane **613**. The return signals **621** illuminate their corresponding photodetector **614**, where they overlap and spatially mix with a corresponding LO signal **609**.

FIG. **16** is a block diagram of an example multi-beam LIDAR system **700** for generating coaxial local oscillator signals at a conjugate plane according to embodiments of the present disclosure. System **700** is similar in all respects to system **600**, except that system **700** includes independent optical windows **607-1** through **607-*n***, which can be adjusted independently with respect to their offset from the first focal plane **606**.

FIG. **17** is a block diagram of an example multi-beam LIDAR system **800** for generating coaxial local oscillator signals at a conjugate plane according to embodiments of the present disclosure. System **800** is similar in all respects to system **700**, except that system **800** includes independent third lens systems **617-1** through **617-*n***.

The preceding description sets forth numerous specific details such as examples of specific systems, components, methods, and so forth, in order to provide a thorough understanding of several examples in the present disclosure. It will be apparent to one skilled in the art, however, that at least some examples of the present disclosure may be practiced without these specific details. In other instances, well-known components or methods are not described in detail or are presented in simple block diagram form in order to avoid unnecessarily obscuring the present disclosure. Thus, the specific details set forth are merely exemplary. Particular examples may vary from these exemplary details and still be contemplated to be within the scope of the present disclosure.

Any reference throughout this specification to "one example" or "an example" means that a particular feature, structure, or characteristic described in connection with the examples are included in at least one example. Therefore, the appearances of the phrase "in one example" or "in an example" in various places throughout this specification are not necessarily all referring to the same example.

Although the operations of the methods herein are shown and described in a particular order, the order of the operations of each method may be altered so that certain operations may be performed in an inverse order or so that certain operation may be performed, at least in part, concurrently with other operations. Instructions or sub-operations of distinct operations may be performed in an intermittent or alternating manner.

The above description of illustrated implementations of the invention, including what is described in the Abstract, is not intended to be exhaustive or to limit the invention to the precise forms disclosed. While specific implementations of, and examples for, the invention are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize. The words "example" or "exemplary" are used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "example" or "exemplary" is not necessarily to be construed as preferred or advantageous over other aspects or designs. Rather, use of the words "example" or "exemplary" is intended to present concepts in a concrete fashion. As used in this application, the term "or" is intended to mean an inclusive "or" rather than an exclusive "or". That is, unless specified otherwise, or clear from context, "X includes A or B" is intended to mean any of the natural inclusive permutations. That is, if X includes A; X includes B; or X includes both A and B, then "X includes A or B" is satisfied under any of the foregoing instances. In addition, the articles "a" and "an" as used in this application and the appended claims should generally be construed to mean "one or more" unless specified otherwise or clear from context to be directed to a singular form. Furthermore, the terms "first," "second," "third," "fourth," etc. as used herein are meant as labels to distinguish among different elements and may not necessarily have an ordinal meaning according to their numerical designation.

What is claimed is:

1. A light detection and ranging (LIDAR) system, comprising:

an optical source to emit an optical beam; and

free-space optics coupled with the optical source to focus the optical beam at a first focal plane, wherein a local oscillator (LO) signal is generated from a partial reflection of the optical beam from a partially reflecting surface proximate to the first focal plane, wherein a transmitted portion of the optical beam is directed toward a scanned target environment, the free-space optics further to focus the LO signal and a target return signal at a second focal plane comprising a conjugate focal plane to the first focal plane, wherein the free-space optics further comprise:

a polarization beam splitter (PBS) to transmit the optical beam to a first lens system, the first lens system to focus the optical beam at the first focal plane;

an optical window comprising the partially reflecting surface, wherein the LO signal is generated from the optical beam and reflected back through the first lens system; and

a photodetector comprising a photosensitive surface proximate to the conjugate focal plane to mix the LO signal with the target return signal to generate target information.

2. The system of claim **1**, wherein the free-space optics further comprise a second lens system, wherein the LO signal is directed through the second lens system by the PBS, the second lens system to focus the LO signal and the target return signal at the second focal plane.

3. The system of claim **2**, wherein the free-space optics further comprise:

a third lens system to collimate the transmitted portion of the optical beam; and

an optical scanner coupled with the third lens system to scan the target environment with the transmitted portion of the optical beam, and to de-scan the target return signal, the third lens system to focus the target return signal at the first focal plane, the first lens system to collimate the LO signal and the target return signal, and the PBS to direct the LO signal and the target return signal to the second lens system.

4. The system of claim **1**, wherein the partially reflecting surface is displaced from the first focal plane.

5. The system of claim **1**, wherein the photodetector is displaced from the second focal plane.

6. A method in a light detection and ranging (LIDAR) system, comprising:

generating an optical beam with a coherent optical source;

transmitting the optical beam through a polarization beam splitter (PBS) and through a first lens system to focus the optical beam at a first focal plane and through an optical window comprising a partially reflecting surface;

focusing the optical beam at the first focal plane;

generating a local oscillator (LO) signal by reflecting a portion of the optical beam from the partially reflecting surface proximate to the first focal plane, wherein a transmitted portion of the optical beam is directed toward a scanned target environment, wherein the LO signal is reflected back through the first lens system;

focusing the LO signal and a target return signal at a second focal plane conjugate to the first focal plane; and

mixing the LO signal with the target return signal in a photodetector proximate to the second focal plane to generate target information.

7. The method of claim **6**, further comprising reflecting the LO signal and the target return signal from the PBS through a second lens system, wherein the LO signal and the target return signal are focused at the second focal plane.

8. The method of claim **7**, further comprising:

collimating the transmitted portion of the optical beam with a third lens system;

scanning the target environment with the transmitted portion of the optical beam;

de-scanning the target return signal; and

focusing the target return signal at the first focal plane with the third lens system.

9. The method of claim **8**, further comprising:

collimating the LO signal and the target return signal with the first lens system; and

directing the LO signal and the target return signal to the second lens system with the PBS, wherein the LO signal and the target return signal are focused at the second focal plane.

10. The method of claim **6**, wherein the partially reflecting surface is displaced from the first focal plane.

11. The method of claim **6**, wherein the photodetector is displaced from the second focal plane.

12. A light detection and ranging (LIDAR) system, comprising:

a processor; and

a non-transitory computer-readable medium storing instructions, that when executed by the processor, cause the LIDAR system to:

focus an optical beam at a first focal plane;

generate the optical beam with a coherent optical source;

transmit the optical beam through a polarization beam splitter (PBS) and through a first lens system to focus the optical beam at the first focal plane and through an optical window comprising a partially reflecting surface;

generate a local oscillator (LO) signal by reflecting a portion of the optical beam from the partially reflecting surface proximate to the first focal plane, wherein a transmitted portion of the optical beam is directed toward a scanned target environment, wherein the LO signal is reflected back through the first lens system;

focus the LO signal and a target return signal at a second focal plane conjugate to the first focal plane; and

mix the LO signal with the target return signal in a photodetector proximate to the second focal plane to generate target information.

13. The system of claim **12**, the LIDAR system further to reflect the LO signal and the target return signal from the PBS through a second lens system, wherein the LO signal and the target return signal are focused at the second focal plane.

14. The system of claim **13**, the LIDAR system further to:

collimate the transmitted portion of the optical beam with a third lens system;

scan the target environment with the transmitted portion of the optical beam;

de-scan the target return signal; and

focus the target return signal at the first focal plane with the third lens system.

15. The system of claim **14**, the LIDAR system to:

collimate the LO signal and the target return signal with the first lens system; and

direct the LO signal and the target return signal to the second lens system with the PBS, wherein the LO signal and the target return signal are focused at the second focal plane.

16. The system of claim **12**, wherein the partially reflecting surface is displaced from the first focal plane.

17. The system of claim **12**, wherein the photodetector is displaced from the second focal plane.

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